GEOPHYSICAL SURVEYS FOR ASSISTING IN DETERMINING THE GROUND WATER RESOURCES ABOVE THE MAKENA GOLF COURSE ISLAND OF MAUI, HAWAII

Blackhawk Geometrics Project Number 9817MRC

Prepared For:
MAKENA RESORT CORPORATION

BLACKHAWK GEOMETRICS

Corporate Center
301 Commercial Road, Suite B,
Golden, Colorado 80401, USA
Tel: (303) 278-8700
Fax: (303) 278-0789

98203MRC
June 18, 1998

Mr. Roy Figueiroa
Makena Resort Corporation
5415 Makena Alanui
Kihei, Maui, Hawaii 96753

RE: Geophysical Surveys for Assisting in Determining the Ground Water Resources Above the Makena Golf Course Island of Maui, Hawaii
Blackhawk Geometrics Project Number 9817MRC

Dear Roy:

Enclosed are (3) three copies of our Final Report for the TDEM surveys above the Makena Golf Course. A copy of the report is being forwarded to Tom Nance.

Mark and I appreciated the opportunity to work with you on this project. We are extremely greatful for the experience that you extended to us on one of the best golf courses on the Hawaii Islands.

Please feel free to call us if you have any questions.

Sincerely,
BLACKHAWK GEOMETRICS

Richard J. Blohm

Richard J. Blohm
Geologist

RB:lm

Enclosures

cc: Tom Nance

GEOPHYSICAL SURVEYS FOR ASSISTING IN DETERMINING THE GROUND WATER RESOURCES ABOVE THE MAKENA GOLF COURSE ISLAND OF MAUI, HAWAII

Blackhawk Geometrics Project Number 9817MRC

Prepared For:

MAKENA RESORT CORPORATION
5415 Makena Alanui
Kihei, Maui, Hawaii 96753
808-879-4455 • Fax 808-879-8530

Prepared By:

BLACKHAWK GEOMETRICS, INC.
301 Commercial Road, Suite B
Golden, Colorado 80401
303-278-8700 • Fax 303-278-0789

June 18, 1998

TABLE OF CONTENTS

1.0 INTRODUCTION

This report contains the results of geophysical surveys conducted to assist in determining the ground water resources above the Makena Golf Course located near Makena, Maui, Hawaii. The surveys were performed by Blackhawk Geometrics (Blackhawk) for the Makena Resort Corporation (MRC) during May 8, 1998. The geophysical method employed during this survey was Time Domain Electromagnetic (TDEM) soundings. The TDEM soundings from this survey and a 1990 survey were located on property owned by MRC above the golf course as shown in Figure 1-1.

The main objective of the geophysical survey was to assist in characterizing the hydrologic regime in the study area for proposed ground water wells. Ground water resources mainly occur on the Island of Maui in two modes:

- In a basal mode where a lens of fresh water floats on saline water, and
- In a high-level mode where the ground water occurrence is controlled by subsurface damming structures.

These two types of ground water occurrences are illustrated in Figure 1-2. The volcanic rocks are generally highly permeable and this allows rainwater to infiltrate directly downward through the island mass. In the Makena area, ground water was expected to occur mainly as a deep basal fresh/brackish water lens. High-level water resources were not expected at the study site.

TDEM investigations conducted for MRC in 1990 were successful in mapping the fresh/brackish basal water lens at the Makena Golf Course. Results from this survey showed a very thin lens (about 10 ft to 50 ft) of fresh/brackish water at the golf course. Several of the soundings were taken near existing water wells and comparisons of the TDEM data to reported ground water levels (heads) in the wells were good. Further inland TDEM surveys near the Ulupalakua Ranch also showed basal water occurrences to exist upslope from the Makena Golf Course. Results from the Ulupalakua Ranch surveys are not included in this study.

2.0 DATA ACQUISITION AND LOGISTICS

The geophysical equipment used for the TDEM surveys was the Geonics EM37 TDEM System. TDEM measurements were acquired using a central-loop sounding array at each site. With this array, measurements are recorded with a receiver coil at the center of transmitter loops laid on the ground surface. The transmitter loops are constructed with 12-gauge insulated copper wire. The dimensions of the square loops employed at the Makena study site were 700 ft by 700 ft. A 2.8 kW transmitter was placed in each sounding loop to drive current ranging from 13 to 14 amperes at base frequencies of 3 Hz and 30 Hz. At the center of each transmitter loop, the time derivative of the vertical magnetic field was recorded with a receiver coil with an effective area of 100 m^2. The data acquired at each sounding consisted of measurements at several receiver gain settings and two transmitter frequencies in order to assure data quality and to obtain data over the largest time interval possible. TDEM data quality was excellent. The data from each sounding was stored in the field on an Omnidata polycorder and, subsequently, transferred to a PC-486 for nightly processing. A technical note describing the principles of TDEM with case histories is given in Appendix A.

During the one day of field work, two soundings were completed over the survey site. A daily log of field activity is given in Table 2-1. The elevation of each sounding center was measured using an Avocet Vertech Altimeter/Barometer. The altimeter was adjusted at landmarks (i.e., bench marks, wells) with known altitudes from a 7.5 minute series topographic map of the Makena area and a detailed 1" to 200 ft topographic map of the study area provided by MRC. The loop locations were selected by representatives of MRC and Blackhawk Geometrics. The sounding locations were based on property ownership, available open land, and exploration objectives and they were measured by compass and hip-chain from known landmarks.

TABLE 2-1 DAILY LOG OF FIELD ACTIVITIES	
DATE, 1998	ACTIVITY
May 1	Mobilize geophysical equipment from Golden, CO, to Maui, HI
May 4	Mobilize Blackhawk Geometrics personnel from Golden, CO, to Maui, HI
May 5	Pick up geophysical equipment from airport & organize into field vehicles. Begin surveys on other Maui projects.
May 6 - 7	Take TDEM data on other Maui projects.
May 8	Meet with MRC representatives and consulting hydrologist to discuss project. Acquire data on Soundings 1 and 2, above the Makena Golf course, along Ulupalakua Road and near rock wall.
May 9 - 14	Data on other Maui projects.
May 15	Demobilize geophysical equipment from Maui, HI, to Golden, CO.
May 23	Demobilize Blackhawk Geometrics personnel from Maui, HI, to Golden, CO.

3.0 DATA PROCESSING

The TDEM field data acquired at the Makena study site were transferred from the Omnidata polycorder to a PC-486. The first step in processing the TDEM data is to average the electromotive forces (emfs) recorded at positive and negative receiver polarities. Next, the recordings made at different amplifier gains and frequencies were combined to give one transient decay curve with the program TEMIXXL (Interpex LTD). With this program, voltages measured with the 20 channels of the Geonics EM37 receiver are transformed into apparent resistivity versus time gate. The apparent resistivity curve is interpreted by inversion to a one dimensional (1-D) geoelectric section that matches the observed decay curve.

The inversion program requires an initial estimate of the geoelectric section, including the number of layers and the thicknesses and resistivities of each of the layers. The program then adjusts these parameters so that the model curve converges to best fit the curve formed by the field data. The inversion program does not change the number of layers within the model, but allows all other parameters to change freely, or they can optionally be fixed constant. To determine the influence and best fit of the number of layers on the solution, separate inversions with different numbers of layers are run. Normally, the model with the fewest number of layers which adequately fits the data is used.

An example of the output of the inversion program is shown on Figures 3-1 and 3-2 for Sounding Maken-1. Figure 3-1 shows the measured data points (in terms of apparent resistivity) superimposed on a solid line. The solid line represents the computed forward model of the geoelectric section shown on the right. Tabulated inversion parameters and results consisting of measured field data, computed data for best match solution, and inversion errors are given on Figure 3-2. The apparent resistivity curves and data sheets for the two Makena TDEM soundings taken during this survey are given in Appendix B.

4.0 INTERPRETATION RESULTS

4.1 General

From TDEM soundings, the resistivity layering (geoelectric section) of the subsurface is derived. The objective of the survey is to infer from the geoelectric sections hydrogeologic information, such as the interface between fresh water and salt water. The translation of resistivity layering into hydrologic information is generally accomplished by two methods. These include:

1) Using available knowledge about the relation between resistivity values and local hydrology. From more than twenty previous TDEM surveys on the Hawaiian Islands, it has been observed that volcanic rocks saturated with salt water exhibit resistivities typically less than 5 ohm-meters (ohm-m). Conversely, unweathered volcanic rocks that are dry or fresh water saturated exhibit high resistivities (generally greater than 500 ohm-m). Weathered volcanics or ash flows and intrusives often exhibit intermediate resistivities (about 10 ohm-m to 100 ohm-m).

   Applying this knowledge, characteristic ranges of resistivities expected for the local hydrogeologic units at the Makena study area are shown in Figure 4-1. It is noted that some overlap in resistivity values occur and in these cases, other factors are used to infer the geologic/hydrologic unit in question. For example, a low resistivity unit (i.e., less than 10 ohm-m) occurring at an elevation above sea level is assumed to be caused by either weathered rock units or intrusives instead of salt water saturated formations.

2) Calibrating the geophysical interpretation at a well. In this case, several wells were used in the 1990 TDEM survey for comparison at the Makena Golf Course. The well locations are shown in Figure 1-1. Wells #2 and #3, located at about the 200 ft elevation level, were successful wells and had reported static water levels (heads) of 1 ft above sea level (asl). Comparison of the TDEM results (Sounding 12) to these wells was good. Another well (above Sounding 11) at the 352 ft elevation level was reported to have a head of 1.1 ft (per. communication with Tom Nance, 1998).

Where a conductive layer (less than 5 ohm-m) is detected below sea level in the TDEM measurement, it is interpreted to be caused by salt water saturated volcanics. Static fresh water levels can be calculated from these soundings by using the Ghyben-Herzberg relation illustrated in Figure 4.2. The Ghyben-Herzberg relation states that for every one foot of fresh water above sea level, approximately 40 ft of fresh water will exist below sea level. However, hydrostatic equilibrium is assumed for these soundings and this relation may not apply to soundings in close proximity to major geologic structures (i.e., rift zones, dikes) which act to alter ground water flow. Typically, rift zones can contain vertical fractures and faults which parallel the main rift corridor for hundreds to sometimes thousands of feet on either side of the central zone. Rift zones can contain a series of volcanic cones which trend linearly away from a caldera.

4.2 Hydrogeologic Interpretation

TDEM soundings at the Makena Golf Course site detected salt water saturated volcanics below sea level. The fresh/brackish water resource can be estimated in these soundings by the volume between sea level and the interpreted elevation of salt water, plus head calculated from the Ghyben-Herzberg relation. Table 4-1 shows the thickness of the fresh/brackish water lens interpreted directly from the model results for each sounding of the present survey and the 1990 survey.

TABLE 4-1
HYDROGEOLOGIC INFORMATION
DERIVED FROM TDEM SOUNDINGS

Sounding # (Year)	Surface Elevation (ft)	Approximate Thickness of Fresh/Brackish Water Lens (ft)
1 (1998)	690	58
2 (1998)	710	14
10 (1990)	220	53
11 (1990)	275	41
12 (1990)	215	19
13 (1990)	280	25
14 (1990)	270	6
15 (1990)	255	45
16 (1990)	190	54
17 (1990)	535	39

The accuracy of determining the depth to sea water from TDEM soundings is estimated to be ±5% of the total depth calculated in the sounding results (e.g., from ground surface to sea water).

The results of the TDEM investigations, from 1990 and 1998, are incorporated into the interpretation summary map shown on Figure 4-3. This map shows contours of interpreted thickness of the basal lens calculated from the TDEM soundings. The contours are approximate because of the low station density. The map shows an increase in the basal water lens thickness from Sounding 2 towards the north (Sounding 1) and west (Soundings 10 and 11). It appears that the results for Sounding 2 are influenced significantly by a structure (volcanic cone from Stearns and Macdonald, 1942) immediately upslope of the sounding. The cone appears to be disturbing (shielding) ground water flow in the vicinity of Soundings 2 and 12. Soundings 10 and 11 showed consistent results when compared to reported heads (1 ft) for Wells #8, #10, and #11. The basal lens thickness also increases to the south of Soundings 2 and 12.

5.0 CONCLUSIONS AND RECOMMENDATIONS

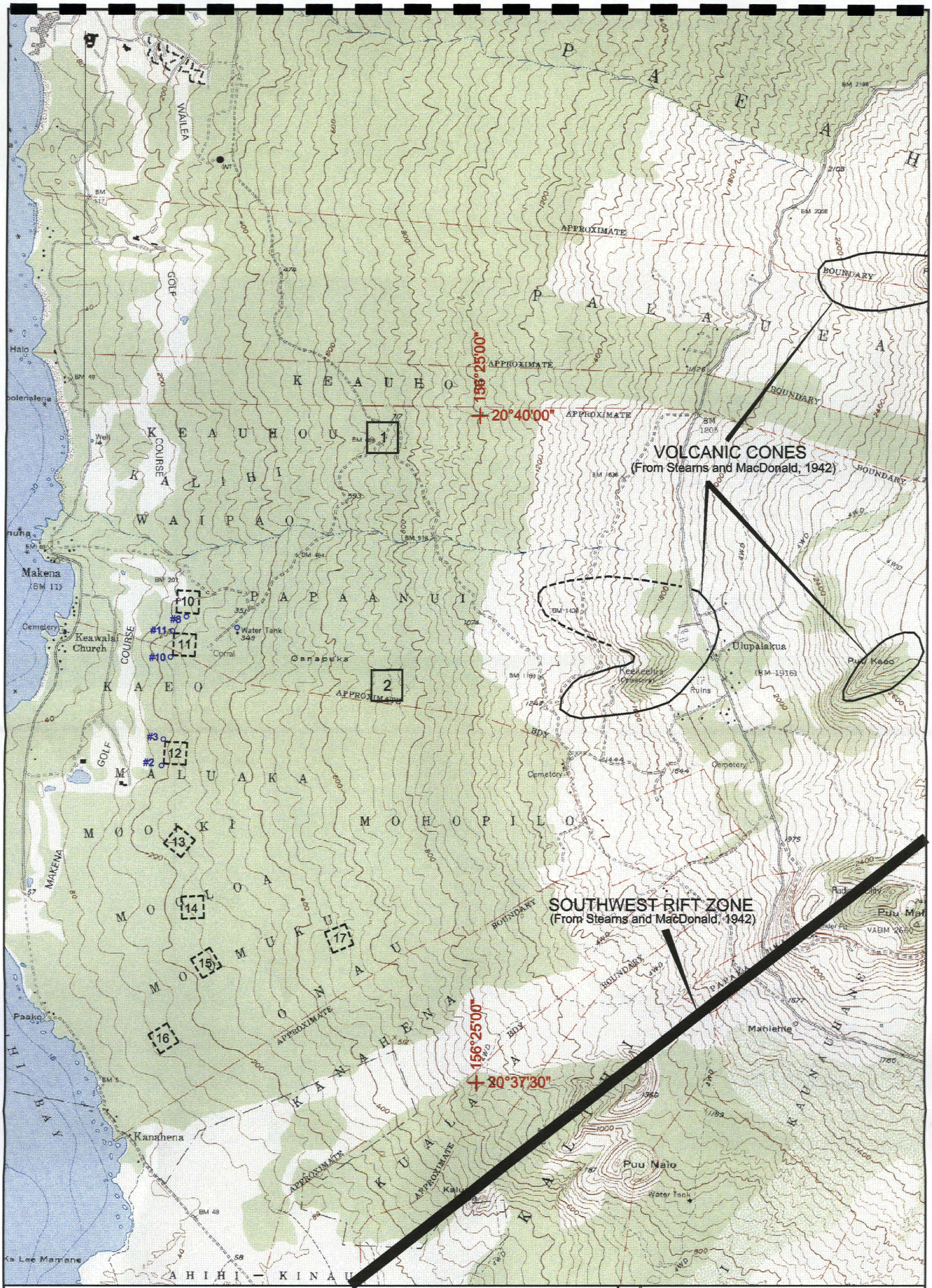
The results of the TDEM surveys above the Makena Golf Course on Maui indicate that a thin basal water resource occurs beneath this portion of the island. The thickest zone of potential fresh/brackish basal water is interpreted to occur beneath Sounding 1, and it is estimated to be 58 ft. The present survey results and previous 1990 data are combined and shown on an interpretation summary map in Figure 4-3. Soundings 2 and 12 show a thin basal lens and lie downhill from a volcanic cone which may affect the ground water flow in this area. To the north and south of Soundings 2 and 12, the basal lens thickness gradually increases.

Soundings 10, 11, and 12 (taken near existing wells) showed good comparisons of calculated lens thickness from TDEM soundings and measured heads. The reported measured heads in Wells #2 and #3 were 1 ft. No high level ground water is indicated in the area of the TDEM soundings.

To improve the reliability of the contours of basal lens thickness, additional TDEM soundings are recommended in areas of limited data. TDEM soundings combined with other hydrogeologic information have proven to be useful in determining optimum locations for well locations and completion depths.

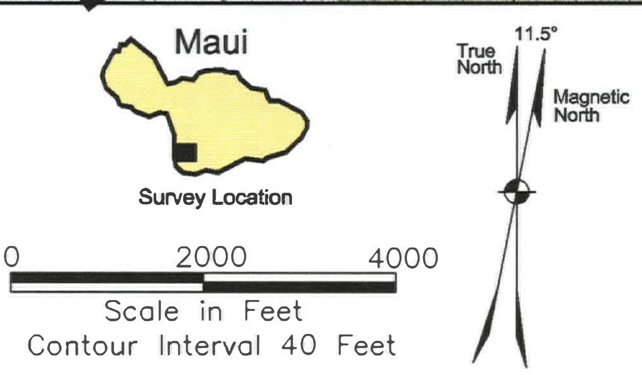
References

1. Davis, S. N., DeWiest, R. J. M., 1966. Hydrogeology: Ground water in igneous rocks. pp. 333-343.
2. Stearns, H. T., Macdonald, G. A., 1942. Geology and ground-water resources of the Island of Maui, Hawaii: Hawaii Division of Hydrography Bulletin 7, pp. 61-81.
3. Takasaki, K. J., 1972. Preliminary report on the water resources of central Maui: Hawaii Division Water and Land Development, Circ. C62, pp. 9-29.
4. Wilt, M. J., 1991. Interpretation of time domain electromagnetic soundings near geologic contacts, Ph.D. Thesis, Lawrence Berkeley Laboratory, University of California Earth Sciences Division. pp. 185.



Explanation

1	1998 TDEM Soundings
10	1990 TDEM Soundings
#8 o	Well Locations



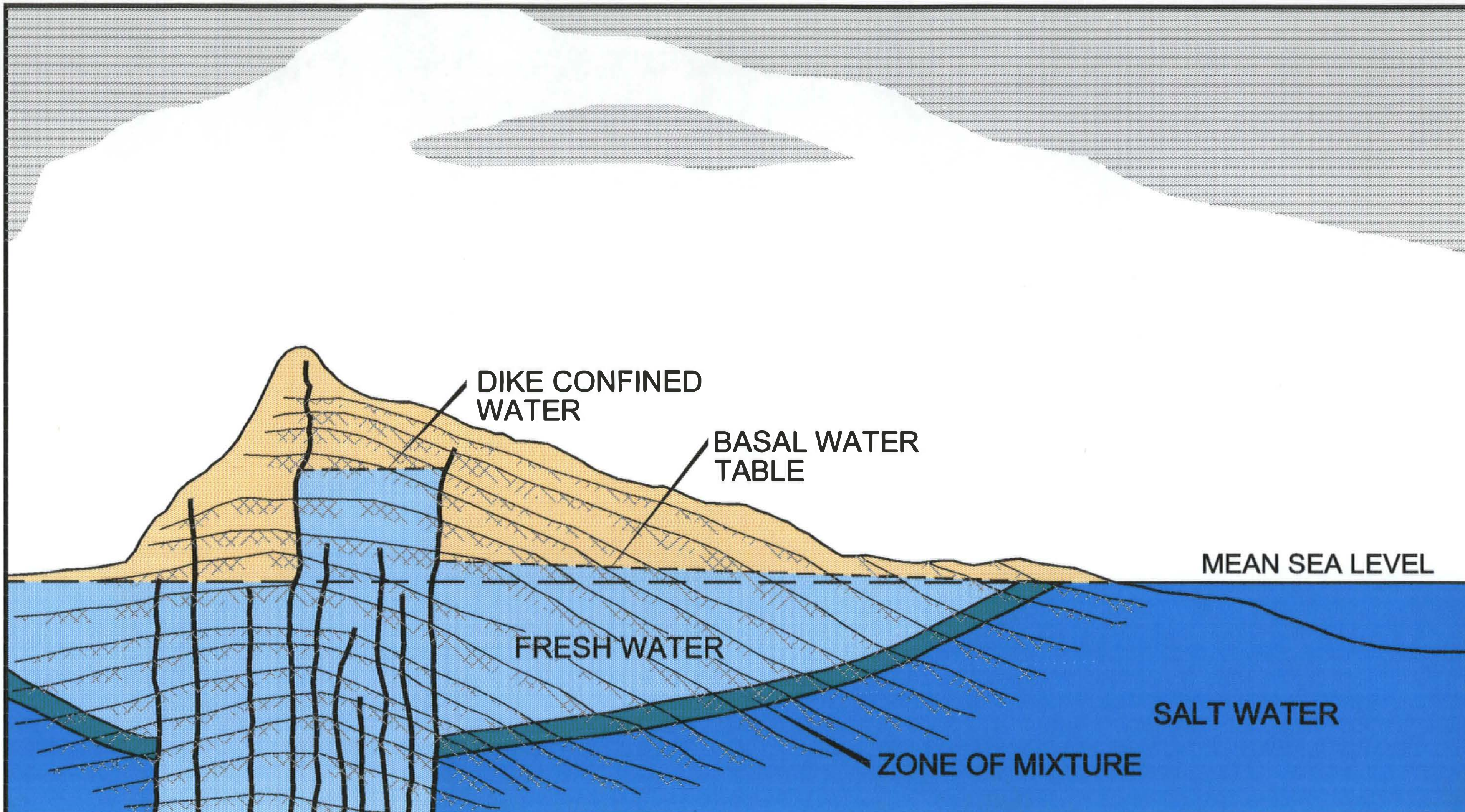
BLACKHAWK GEOMETRICS

Location Map
Makena Golf Course

Makena Resort Corporation
Makena, Maui, Hawaii

Project No. 9817 Figure: 1-1

\projects\Maui98\9817mrc\LocMap.dwg



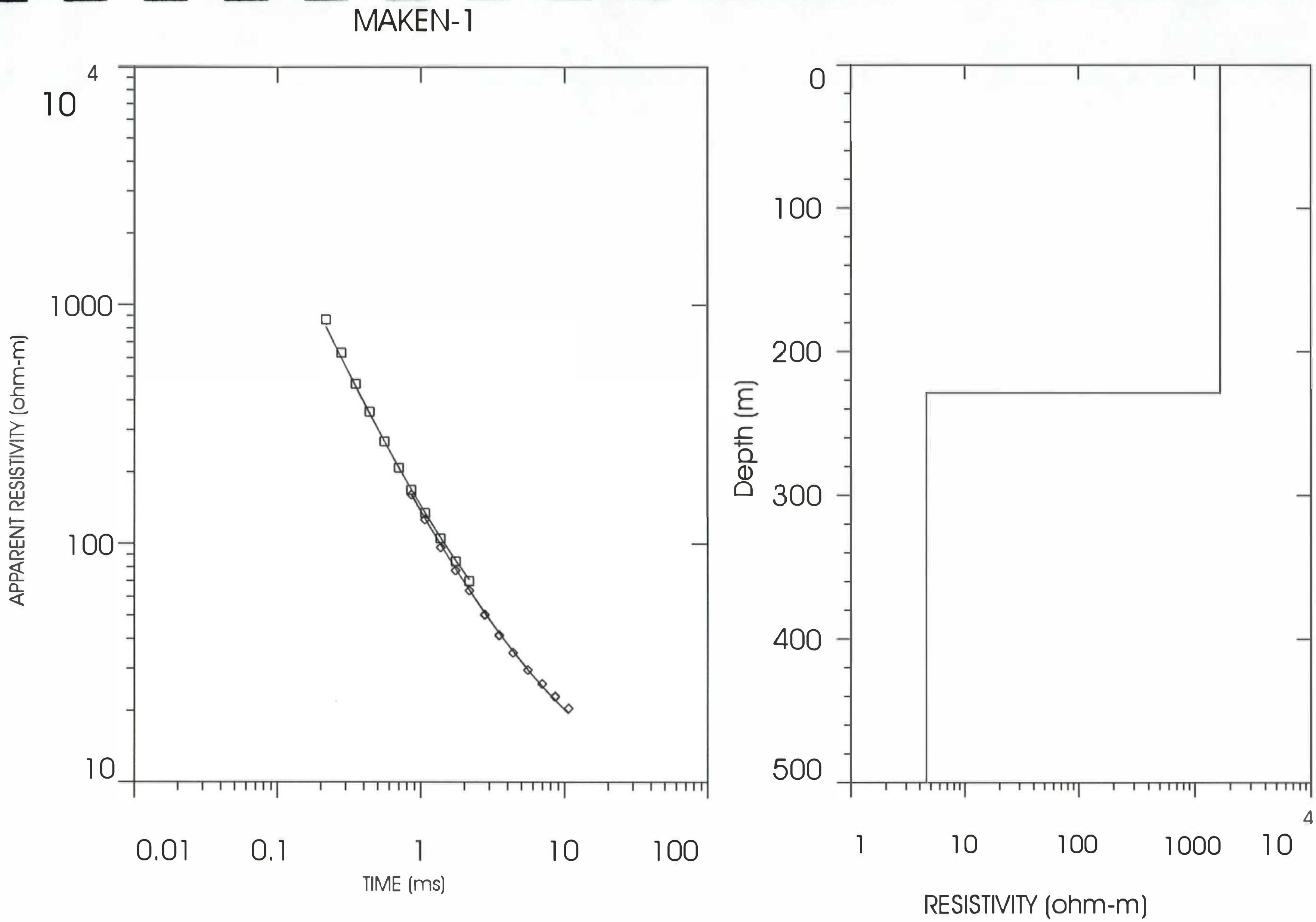
BLACKHAWK GEOMETRICS

Schematic
Hydrogeologic Cross Section

Makena Resort Corporation
Makena, Maui, Hawaii

Project No. 9817 Figure: 1-2

\projects\Maui98\9817mrc\WtrXsec.dwg



BLACKHAWK GEOMETRICS

TDEM Inversion Results
Sounding MAKEN-1
Makena Resort Corporation
Makena, Maui, Hawaii

Figure: 3-1

Project No. 9817

\projects\maui98\9817mrc\Results1.cdr

DATA SET: MAKEN-1

CLIENT: MAKENA RESORTS CORP — DATE: 05-08-98
LOCATION: MAKENA, MAUI — SOUNDING: 1
COUNTY: MAUI — ELEVATION: 210.00 m
PROJECT: MAKENA IRRIGATION WELLS — EQUIPMENT: Geonics PROTEM
LOOP SIZE: 213.000 m by 213.000 m — AZIMUTH:
COIL LOC: 0.000 m (X), 0.000 m (Y) — TIME CONSTANT: NONE
SOUNDING COORDINATES: E: 100.0000 N: 1.0000 SLOPE: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 3.876 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	CONDUCTANCE (Siemens)
			210.0	
1	1657.4	228.6	-18.60	0.137
2	4.58			

ALL PARAMETERS ARE FREE

CURRENT: 14.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 7 RAMP TIME: 120.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.218	562.4	619.4	-10.12
2	0.278	495.2	526.6	-6.33
3	0.351	431.9	445.8	-3.20
4	0.438	372.0	377.2	-1.39
5	0.558	312.1	310.1	0.651
6	0.702	257.1	254.5	1.02
7	0.858	214.8	211.7	1.44
8	1.06	173.6	171.3	1.33
9	1.37	134.4	131.8	1.97
10	1.74	102.7	100.7	2.00
11	2.17	78.95	77.08	2.36

CURRENT: 14.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 7 RAMP TIME: 120.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
12	0.857	230.1	226.7	1.48
13	1.06	191.2	185.6	2.91
14	1.37	152.6	145.4	4.74
15	1.74	117.1	113.5	3.03
16	2.17	90.19	89.09	1.21
17	2.77	69.54	67.05	3.56
18	3.50	52.22	50.22	3.82
19	4.37	38.57	37.59	2.53
20	5.56	27.10	26.97	0.469
21	6.98	18.78	19.38	-3.22
22	8.56	13.56	14.20	-4.75
23	10.64	9.30	10.04	-7.94

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

	P 1	P 2	T 1
P 1	0.01		
P 2	-0.03	0.90	
T 1	0.01	0.00	1.00

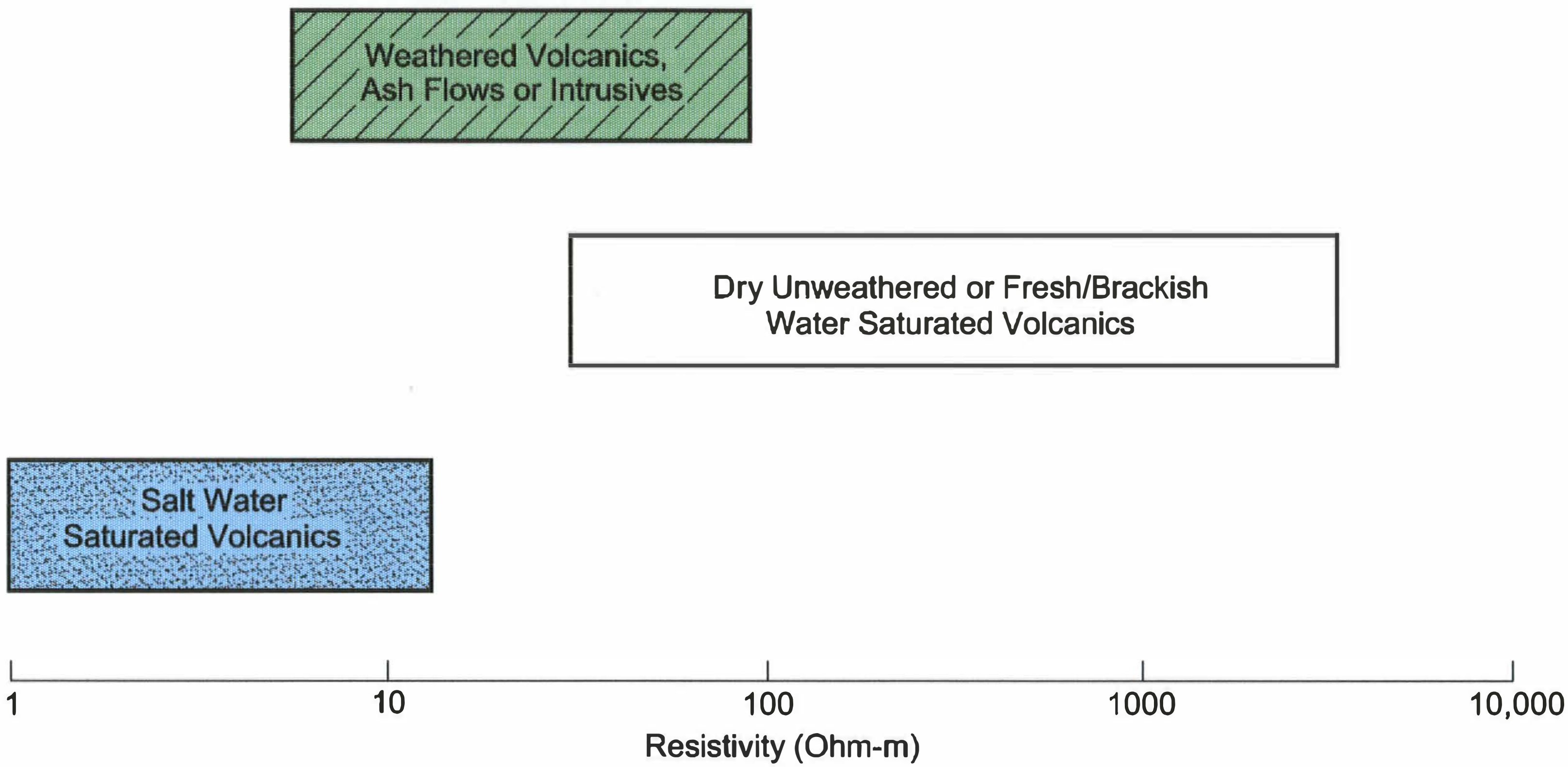
BLACKHAWK GEOMETRICS

TDEM Inversion Results
Sounding MAKEN-1
Makena Resort Corporation
Makena, Maui, Hawaii

Figure: 3-2

Project No. 9817

projects\maui98\9817mrc\Results2.cdr



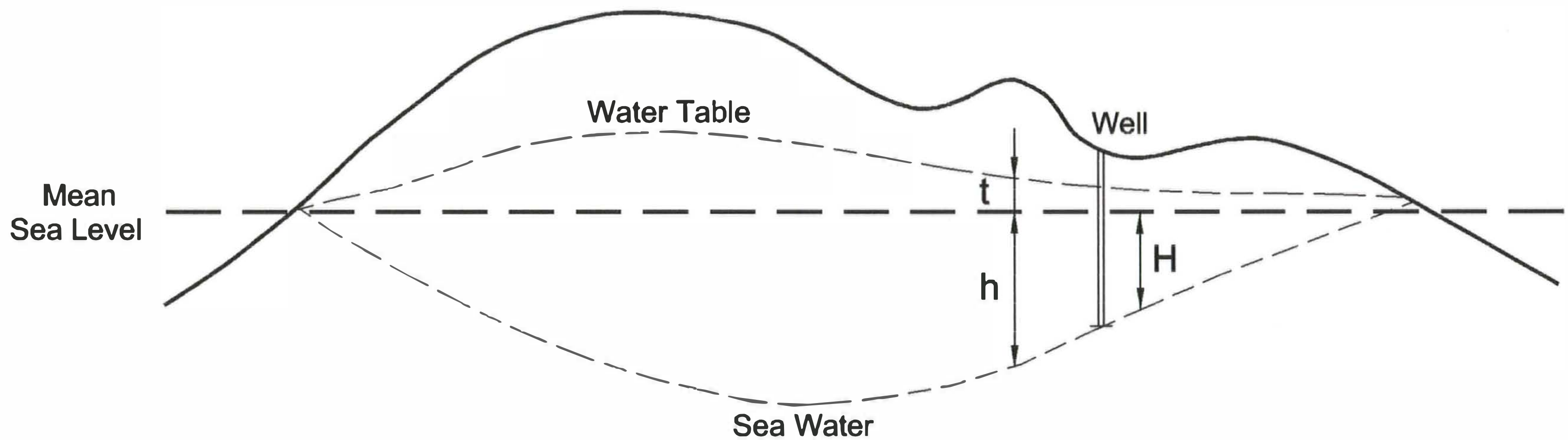
BLACKHAWK GEOMETRICS

Characteristic Resistivity Ranges

Makena Resort Corporation
Makena, Maui, Hawaii

Project No. 9817 | Figure: 4-1

\projects\Maui98\9817mrc\WtrXsec.dwg



$t = 1/40\ (h)$

From: Herzberg

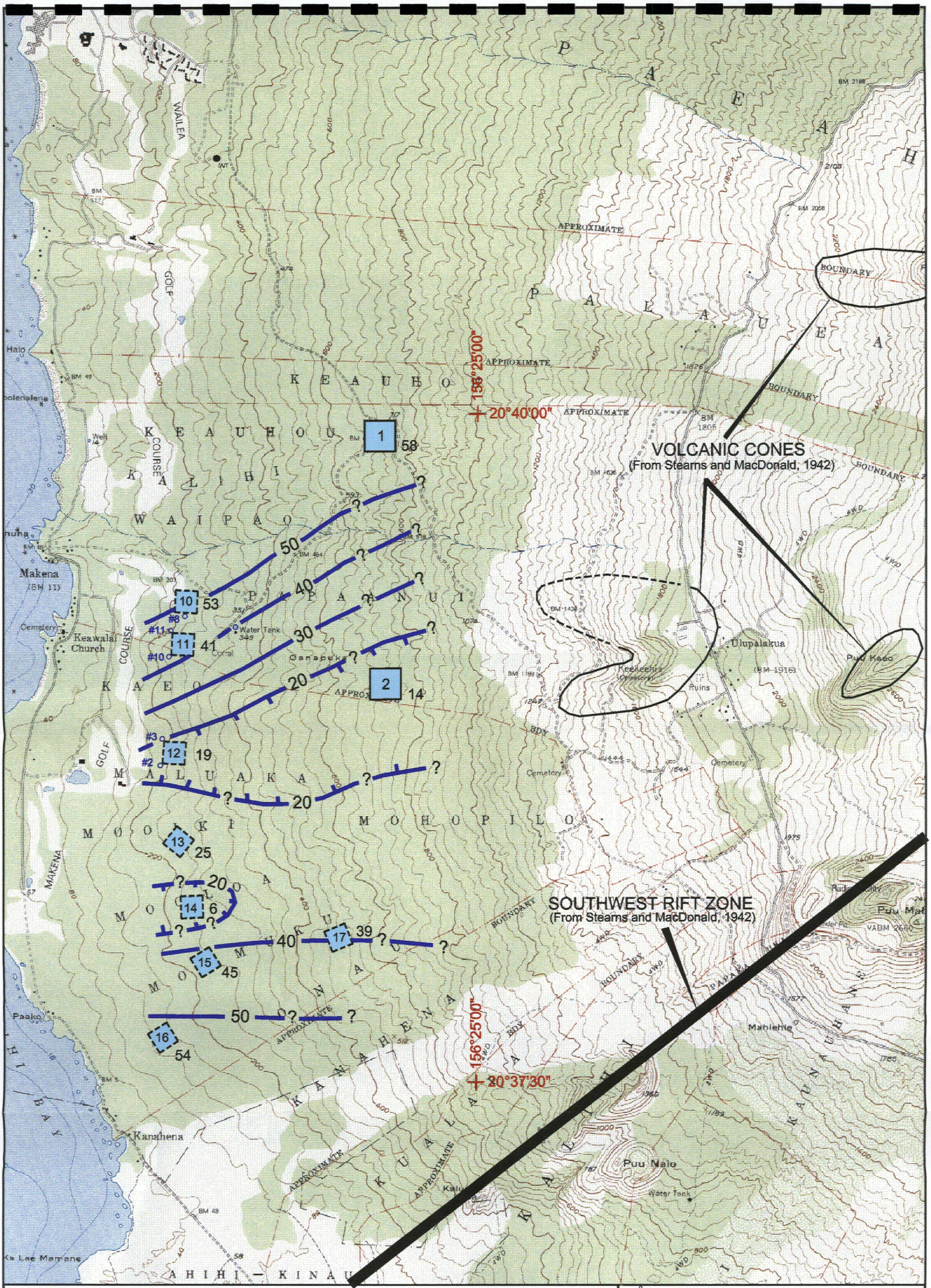
BLACKHAWK GEOMETRICS

Illustration of the
Ghyben-Herzberg Principle

Makena Resort Corporation
Makena, Maui, Hawaii

Project No. 9817 Figure: 4-2

\projects\Maui98\9817mrc\WtrXsec.dwg



Explanation

- Sounding in which ground water is expected in basal mode
- 58 — Approximate thickness of basal water lens
- Contours of basal lens thickness
- 1 — 1998 TDEM Soundings
- 10 — 1990 TDEM Soundings
- #8 ○ — Well Locations

Maui

Survey Location

0 2000 4000

Scale in Feet

Contour Interval 40 Feet

True North

Magnetic North

11.5°

BLACKHAWK GEOMETRICS

Summary Map
Makena Golf Course

Makena Resort Corporation
Makena, Maui, Hawaii

Project No. 9817 | Figure: 4-3

\projects\Maui98\9817mrc\SumMap.dwg

Case Histories of Time-Domain Electromagnetic Soundings in Environmental Geophysics

Pieter Hoekstra and Mark W. Blohm**

Abstract

Time-domain electromagnetic (TDEM) soundings are a surface electromagnetic technique that finds increasing use in environmental geophysics. Commercial equipment is now available for TDEM soundings in the exploration depth range from about 5 m to about 5000 m. Application of TDEM is illustrated in three case histories.

The transmitter-receiver array used in all three investigations was the central-loop array, in which measurements of the electromotive force due to the vertical magnetic field are made with a receiver in the center of square, nongrounded transmitter loops. The dimensions of the transmitter loops were varied from 30 m by 30 m for effective exploration depths between 5 m to 75 m, to 500 m by 500 m for effective exploration depths to about 2500 m. These relatively small dimensions of receiver/transmitter arrays, compared to the exploration depth, allow TDEM surveys to be made in urban areas where open spaces are limited in size, and where environmental and ground-water problems are perhaps most urgent. Also, the procedures of signal processing used in TDEM facilitate operation in the presence of high ambient electrical noise prevalent in urban settings.

The three case histories map:

(1) the depth of first occurrence of brine for assisting site evaluation of a high-level nuclear-waste repository in bedded salts near Carlsbad, New Mexico,

(2) the encroachment of salt water in a multiple-zone coastal aquifer system in the Salinas Valley, California, (The availability of about 100 monitoring wells allowed correlation of formation resistivities to ground-water salinity.) and

(3) shallow basalt flows in the exploration depth range from 5 m to 30 m. (This case history shows the results of TDEM measurements over the time range from about 10^{-6} s to 10^{-4} s with central-loop soundings of small (30 m) dimensions.)

Introduction

Time-domain electromagnetic (TDEM) soundings increasingly are being employed for determining geoelectrical sections. Reported applications of this TDEM method are in mapping of volcanic cover (Frischknecht and Raab, 1984; Keller et al., 1984), onshore and offshore permafrost (Ehrenbard et al., 1983), geothermal reservoirs (Fitterman et al., 1988), hydrocarbons (Rabinovich et al., 1977; Wightman et al., 1983), and ground water (Fitterman and Stewart, 1986; Mills et al., 1988). Theoretical aspects of the method, such as behavior of magnetic and electric fields (e.g., Nabighian and Oristaglio, 1984), definition of apparent resistivity (Kaufman and Keller, 1983; Spies and Eggers, 1986), transmitter-receiver arrays (Kaufman and Keller, 1983), and influence of two-dimensional (2-D) and three-dimensional (3-D) structures on one-dimensional interpretations (Hohmann, 1988; Newman et al., 1987) are discussed throughout the geophysical literature [see also McNeill, Vol. I—Ed.].

Several reasons are apparent for the increasing use of TDEM in environmental geophysics. In urban areas ambient electrical noise is high, and open spaces limited. TDEM surveys can often work around these limitations. Small transmitter-receiver arrays can be laid out in athletic fields, parks, and other open spaces, and ambient

*Blackhawk Geosciences, Inc., 17301 West Colfax, #50, Golden, CO 80401.

electrical noise due to residential power service can often be removed by stacking. Also, recent availability of equipment with fast, current ramp turn-off and early-time measurements bring shallow mapping objectives for ground-water protection and contaminant investigations within the exploration depth range of TDEM.

A limitation of TDEM at this time is the lack of practical, cost-effective algorithms for interpreting 2-D and 3-D structures. At present, forward modeling of 2-D and 3-D structures (Newman et al., 1987), requires significant central processing unit (CPU) time on the mainframes negating their application to shallow TDEM exploration. It is in the development of practical algorithms for 2-D and 3-D interpretations for personal computers that the main advances in TDEM must come.

Illustrated applications of the method to three environmental objectives include (1) assisting in siting of high-level, nuclear-waste repositories, (2) mapping the intrusion of salt water in coastal aquifers, and (3) mapping the thickness of thin basalt flows. The basic principles of the equipment and the procedures of data acquisition and processing are similar for all three case histories. Some characteristics of central-loop array measurements, such as land survey requirements, location of plotting points, and vertical resolution are reviewed briefly. Equipment design parameters and data acquisition, processing, and interpretation procedures are discussed. These principles are illustrated subsequently on the three case histories. The Geonics EM-47, EM-37 or EM-42 were used in acquiring the data for all three case histories.

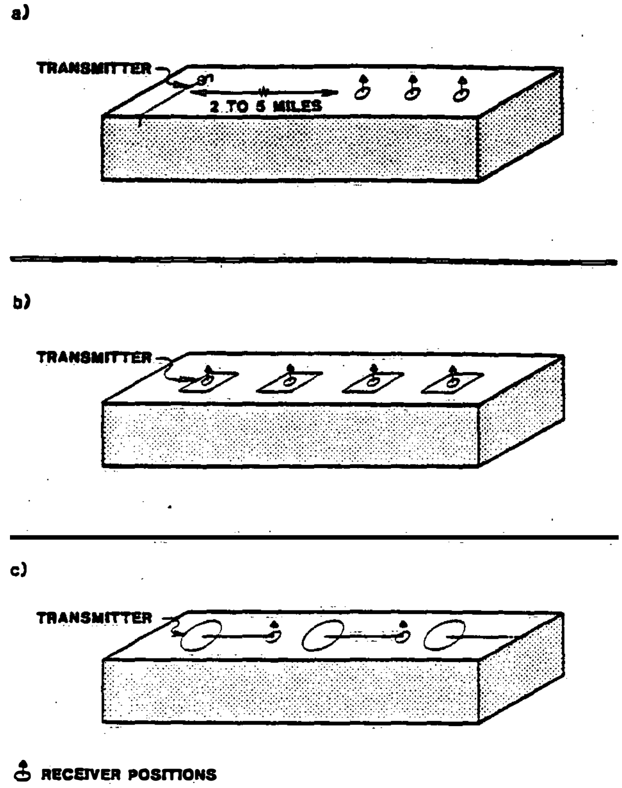


FIG. 1. Transmitter-receiver arrays, (a) grounded line, (b) central loop, and (c) loop-loop.

Practical Aspects of Data Acquisition

Transmitter-Receiver Arrays

The three types of transmitter-receiver arrays employed in TDEM soundings are illustrated in Figure 1. The array used in the three case histories is the central loop array (Figure 1b). For applications in environmental geophysics there are certain advantages to the central loop array, such as:

(a) Land survey and space requirements.—Figure 2 shows the measured behavior of the electromotive forces (emf's) due to horizontal (x) and vertical (z) magnetic field components on a profile through the center of a square transmitter loop at 2.2 ms after current turn-off. Data at other times would show a similar behavior but differ in amplitudes. The emf due to the z-component can be seen to be relatively flat about the center. Location errors of $\pm 10\%$ L (L is side of square) cause negligible errors, and deviations from a square transmitter loop have little effect on a data set. Because in central loop soundings the geoelectric section is derived from emf$_z$, requirements for accurate positioning are minimal which enhances the practical value of field survey productivity, and allows flexibility in choosing a station location. Because emf$_x$ has a zero crossing in the center of the loop, its measurement would require careful survey control. Also, ambient electrical noise is higher in horizontal components.

The dimensions of transmitter loops in central-loop arrays depend on required exploration depth, exploration objective, and geoelectric section. Optimum dimensions are generally selected from forward modeling and field tests. Typically, the length of a side of the transmitter loop is about two-thirds of the exploration depth for the EM-37. The EM-42 is generally employed for exploration depths from about 300 m to 2500 m with 500 m by 500 m transmitter loops, and with a grounded line array for deeper objectives.

The grounded line array (Figure 1a) with long offset receiver locations is dominantly used in deep electrical soundings in support of oil and gas exploration (Keller et al., 1984). The loop-loop array (Figure 1c) finds ap-

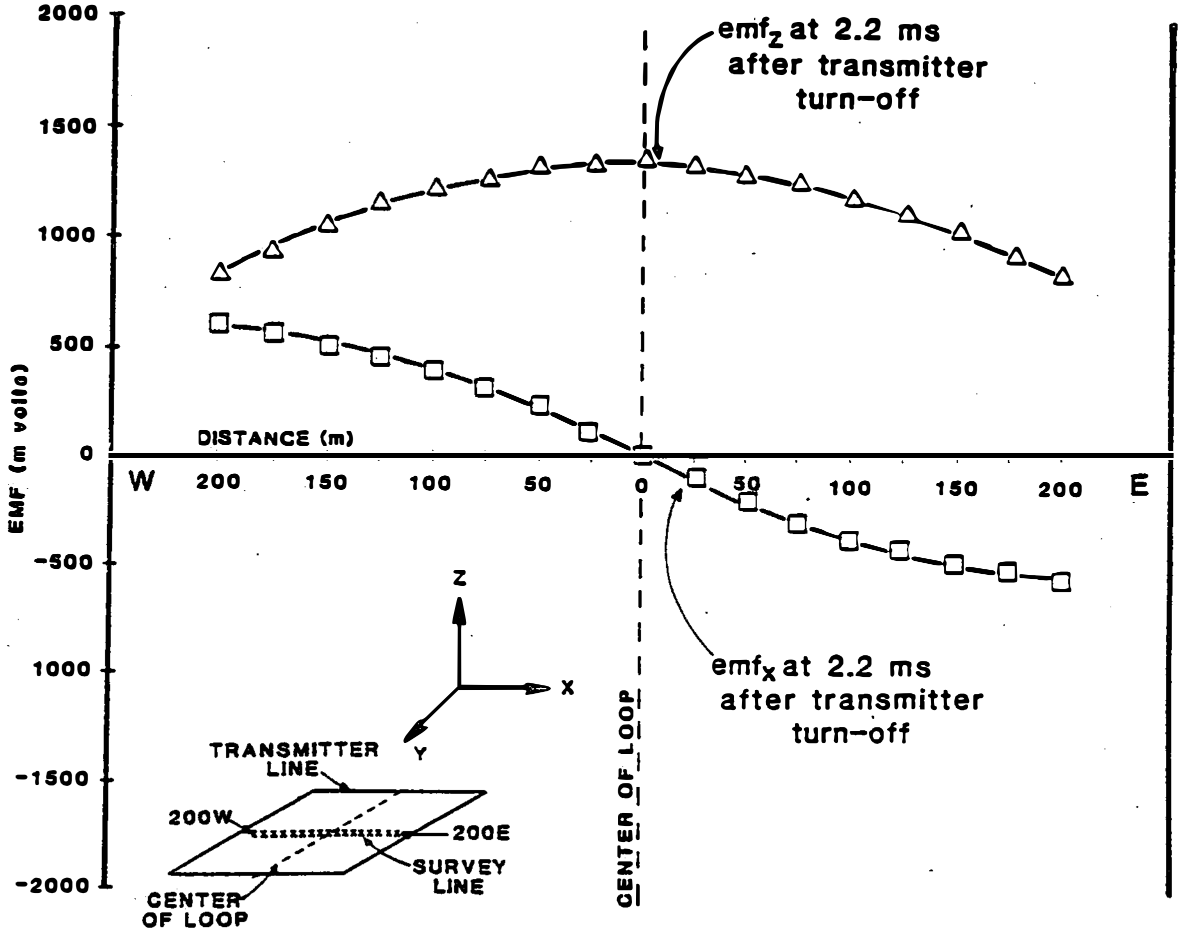


FIG. 2. Measured behavior of the electromotive forces due to vertical (emf$_z$) and horizontal (emf$_x$) magnetic fields on a profile through the center of a square transmitter loop.

plication in mineral exploration and in mapping of fractures and shear zones.

(b) Well-defined sounding plotting points.—The behavior of induced eddy currents and the resulting behavior of the secondary magnetic fields in horizontally-layered media are well documented (Kaufman and Keller, 1983; Ward and Hohmann, 1988). They show a current distribution diffusing downward and outward from the source. For nongrounded, square-loop transmitters currents are symmetrically distributed about the center. Therefore, the center is a well-defined plotting point.

In the grounded-line array or loop-loop array the entire section between transmitter and receiver is expected to influence the measurements, although subsurface conditions near the receiver may have a larger influence on emf$_z$ measured. The correct plotting point of a station is not well defined. Some place the plotting point below the receiver (Keller et al., 1984) and others midway between the transmitter and receiver (Rabinovich and Surkov, 1978). This same situation prevails in loop-loop arrays. In frequency-domain loop-loop arrays the midpoint of the array has traditionally been used as the plotting point.

(c) Vertical resolution.—Kaufman and Keller (1983) show that (1) the asymptotic behavior of emf$_z$ at late time, is given by

$$\mathrm{emf}_z = \frac{\mu^{5/2}}{4\pi^{3/2}} \frac{\sigma^{3/2} M_t M_R}{t^{5/2}}; \qquad (1)$$

where

t = time after current turn-off,
σ = conductivity of uniform half-space,
μ = magnetic susceptibility,
M_t = moment of transmitter,
M_R = moment of receiver;

and (2) that this asymptotic expression describes the emf over the time range given by;

$$\frac{\tau}{R} > 16, \qquad (2)$$

where

$$\tau \text{ is } \sqrt{\frac{8\,\pi^2 t}{\mu_0\,\sigma}}.$$

Figure 3 is a nomograph showing the onset of "late stage" behavior ($\tau/R > 16$), as a function of resistivity, and time at several values of R. Also shown on Figure 3 are the time ranges of measurement for the three systems used in the case histories. In central loop soundings typical values of R are between 15 m and 250 m, so that over a large time range of measurements emf$_z$ is proportional to $\sigma^{3/2}$. This high sensitivity of the quantity measured (emf$_z$) to the geoelectric section often results in a reduced range of equivalence for certain sections compared to other electrical and electromagnetic techniques (Fitterman et al., 1988).

Equipment

The Geonics EM-47, EM-37 or EM-42 were used in acquiring the data for all three case histories. All three sets of equipment use the current waveform illustrated in Figure 4, consisting of equal periods of time-on and time-off. Figure 5 illustrates the difference in data acquisition between the EM-47 and EM-37, and the EM-42. In the EM-47 and EM-37 an analog stack is performed, and after completion of the stacking and A/D conversion, the data are stored in solid state memory. Normally, at the completion of a survey day, the data are transfered to a computer for data processing, plotting, and interpretation. During field operations no real-time processing is available. Minimum detectable signal in typical, urban, ambient-noise environments is 10^{-9} V/A-m^2 (normalized by current in transmitter loop, and effective area of receiver coil).

In the EM-42 the transient is sampled at 400 μs intervals, and these samples are digitally stored on 1/2-inch, 9-track tape. "Smart stacking" is applied to the data in real time. The minimum detectable signal with

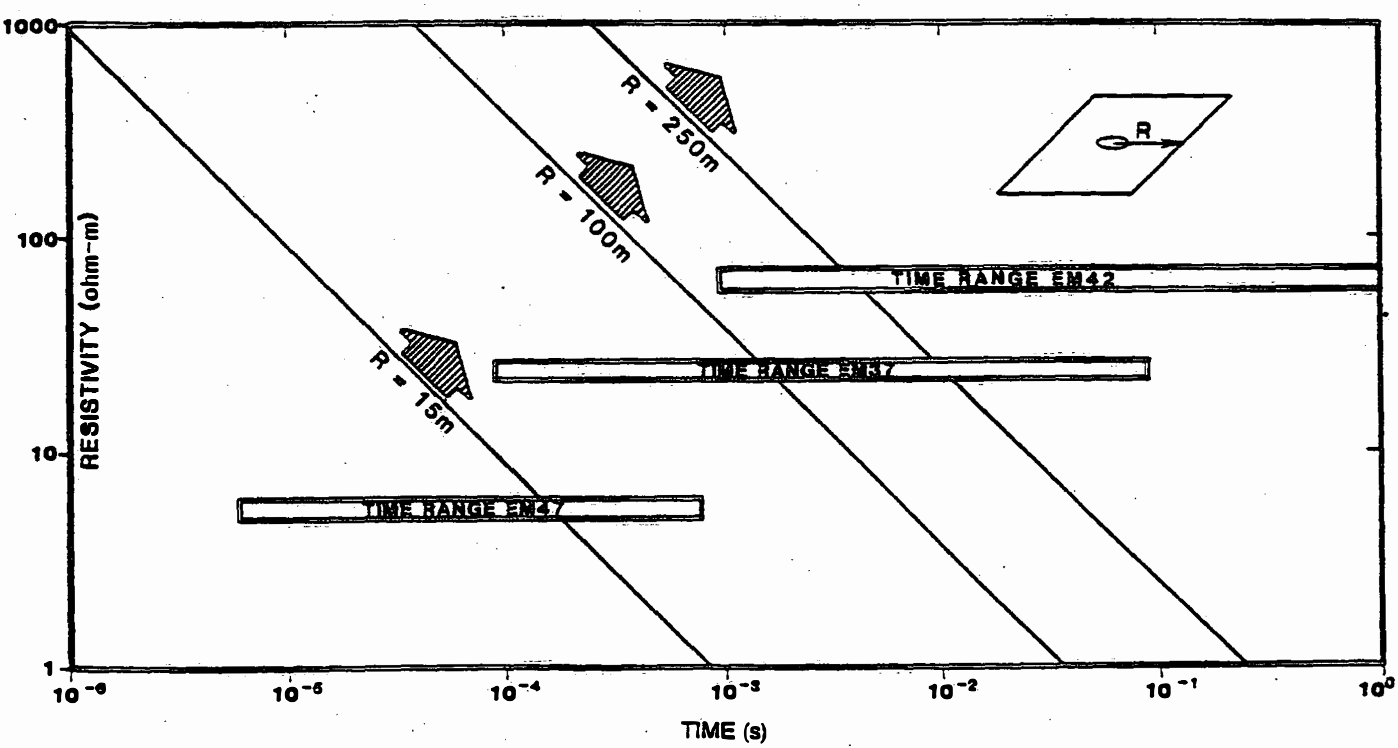


FIG. 3. Nomograph showing onset of late stage behavior for central-loop array as a function of time and resistivity of uniform half-space.

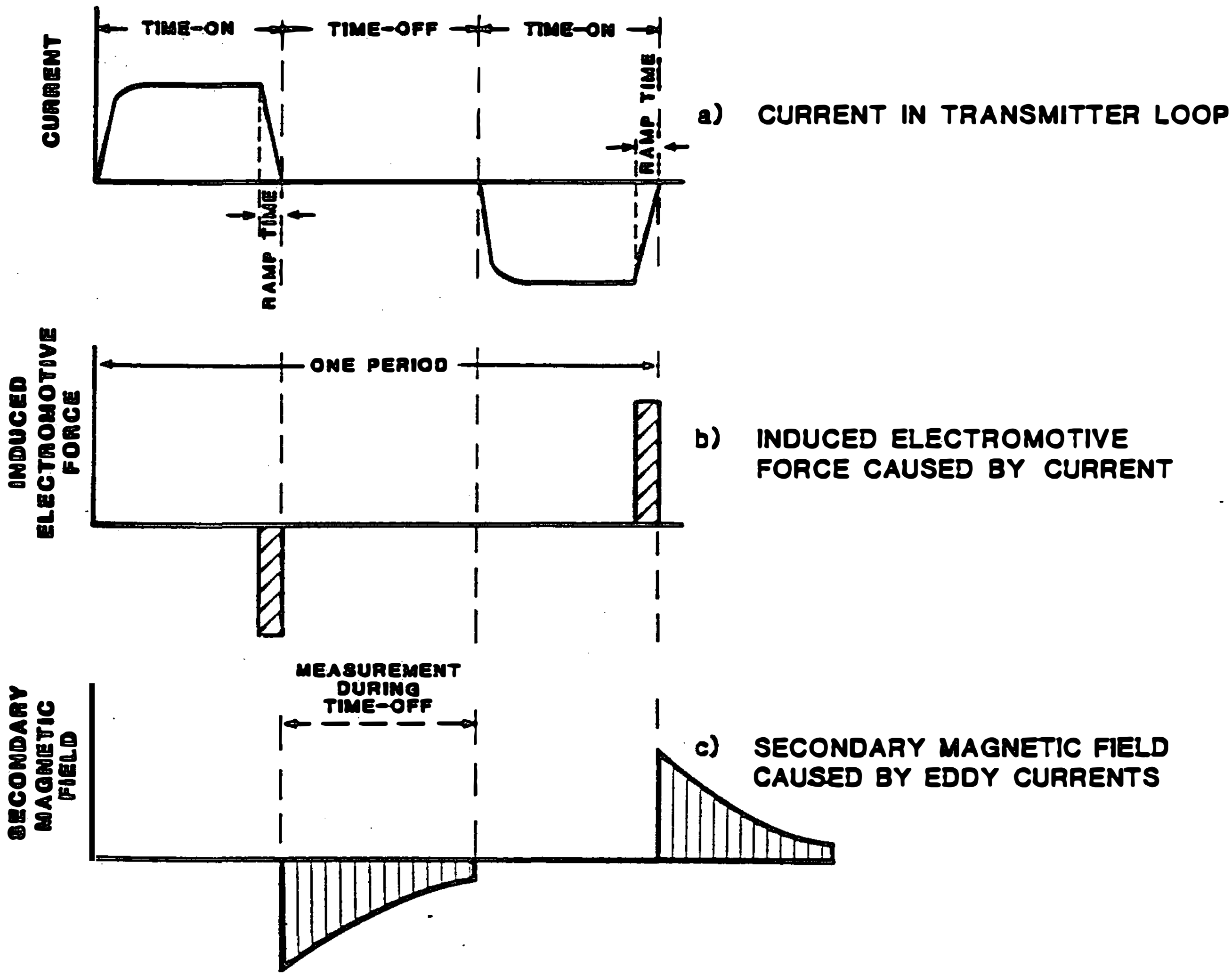


FIG. 4. System waveforms employed in Geonics EM-47, EM-37, and EM-42.

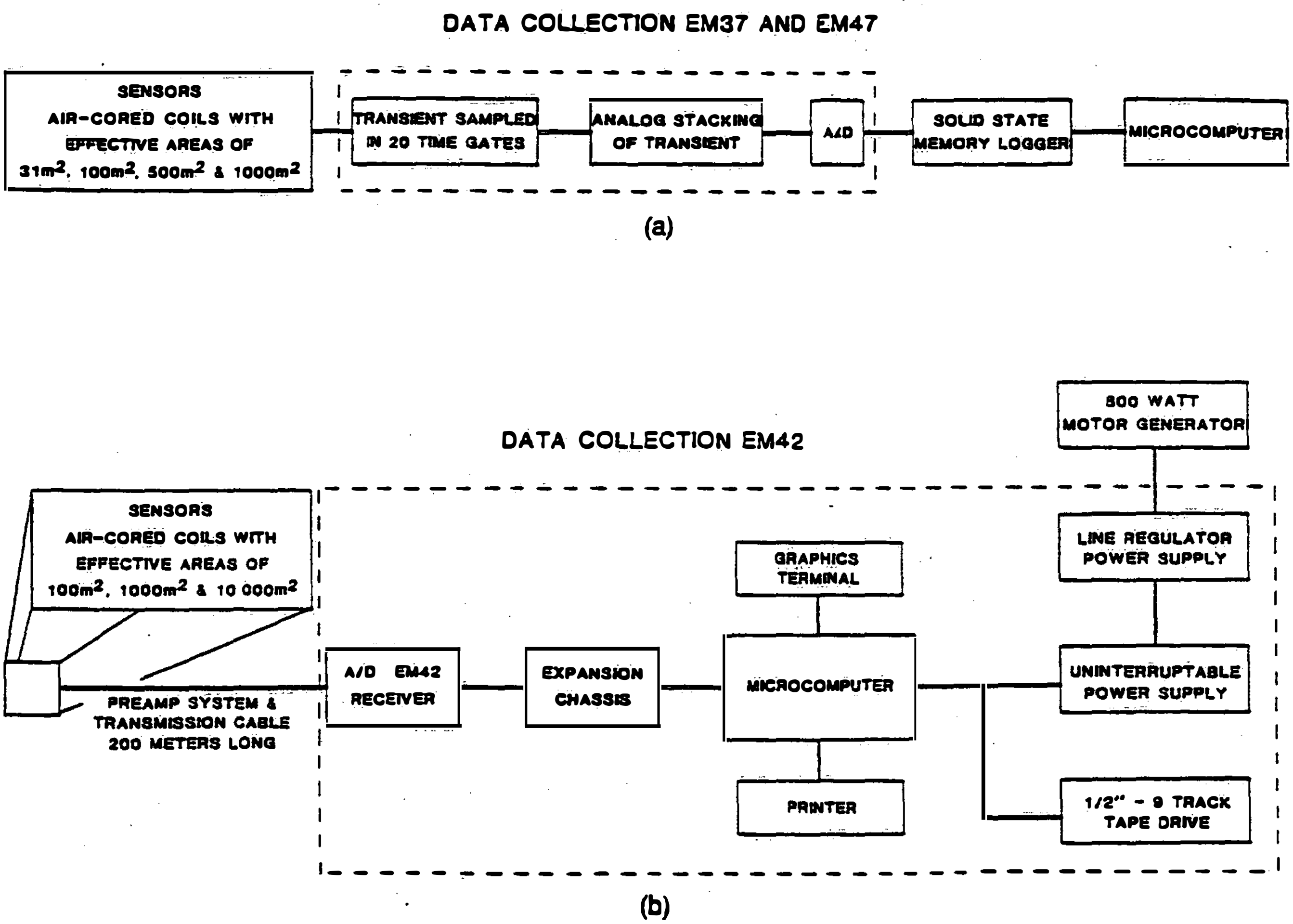


FIG. 5. Block diagrams of TDEM systems.

the EM-42 in typical ambient noise environments is 10^{-12} V/A-m^2

Data Acquisition

Recording transient decays with central loop soundings requires a large dynamic range, because emf, decays as $t^{-5/2}$, as shown in equation (1). This large dynamic range is often obtained by acquiring a data set in segments using different combinations of base frequencies, gains, and air coil receivers. An example of such a data set is given in Figure 6. The early time part of the curve was acquired at a base frequency of 3 Hz, 100 m^2 air coil and EM-37 receiver; the later time section was recorded with the EM-42 receiver, a 10 000 m^2 air coil and a base frequency of 0.075 Hz. When the 10 000 m^2 coil is used, the early time segment of this curve is purposely saturated. It is common to collect data sets at two receiver polarities, various gain settings, base frequencies, and with receiver coils of different effective areas. These various data sets are combined in one transient-decay curve that is subsequently entered into inversion routines.

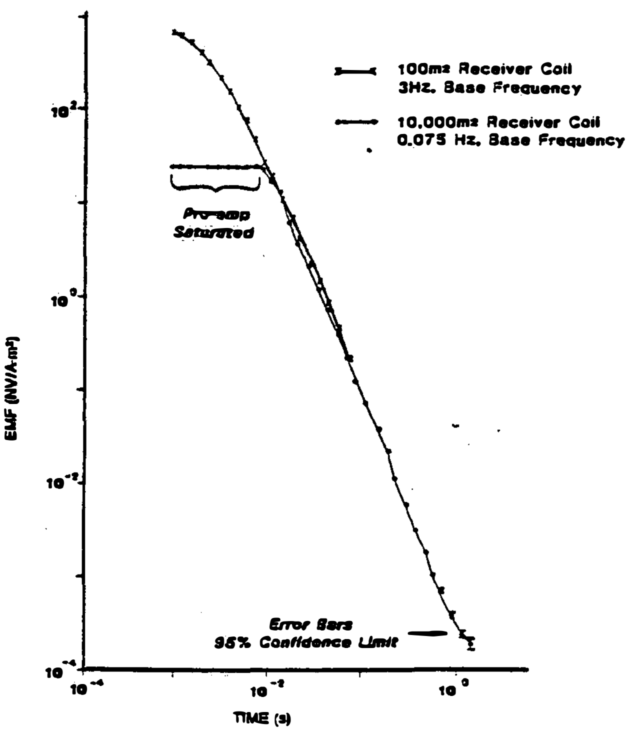


FIG. 6. Emf, measured in center of 500 m by 500 m transmitter loop.

Definition of Apparent Resistivity

All electrical and electromagnetic methods commonly transform the voltages or emf's measured into apparent resistivities. In TDEM several definitions of apparent resistivity are in use (Kaufman and Keller, 1983; Goldman, 1988) and the merits and pitfalls of the various definitions have been reviewed in Spies and Eggers (1986). These pitfalls are often avoided by (1) integrating inversions with available geologic data, and (2) using albums of forward-model curves for first-guess solutions. In all the case histories late-stage (Kaufman and Keller, 1983) apparent resistivity curves are used. Two reasons for that selection were (1) over a large range of time late-stage behavior is observed in central-loop soundings, and (2) extensive volumes of late-stage model curves (Goldman and Rabinovich, 1974) are available.

Data Interpretation

All the examples shown in the case histories were interpreted by one-dimensional (1-D) inversions of the data using a ridge-regression inversion program (ARRTI, Interpex Ltd, 1985). The input for the program are the emfs measured in various time gates, certain equipment and survey parameters (transmitter loop size, current, ramp time, receiver coil effective area), and number of layers to be used in the inversion. Also, an initial solution is entered. Goldman (1988) discussed the dependence of inversion routines on this first guess. To mitigate convergence to unrealistic solutions, first guesses are made to correspond with known geologic conditions, and depending on the quality of available geologic information, certain parameters in a geoelectric section may be fixed at specific values, e.g., as observed in borehole logs.

In TDEM soundings there is merit in carefully considering inversion errors at each time gate, because each section of the curve is often diagnostic of a certain depth section (Kaufman and Keller, 1983; Raiche and Gallagher, 1985). This can be illustrated by a central loop TDEM sounding with a 500 m by 500 m transmitter loop over a Tertiary valley fill in Nevada. Figure 7b shows the late-stage, apparent resistivity curve and Figure 7a two 1-D inversions for this sounding. The difference between the two inversions is the absence of a resistive layer (basalt flow) in section 1, and its presence in section 2. Figure 7c shows the error between the measured data and the two inversions. The increased error over the early time range suggested inserting an additional layer into the inversion. The existence of this resistive layer has been confirmed by drilling.

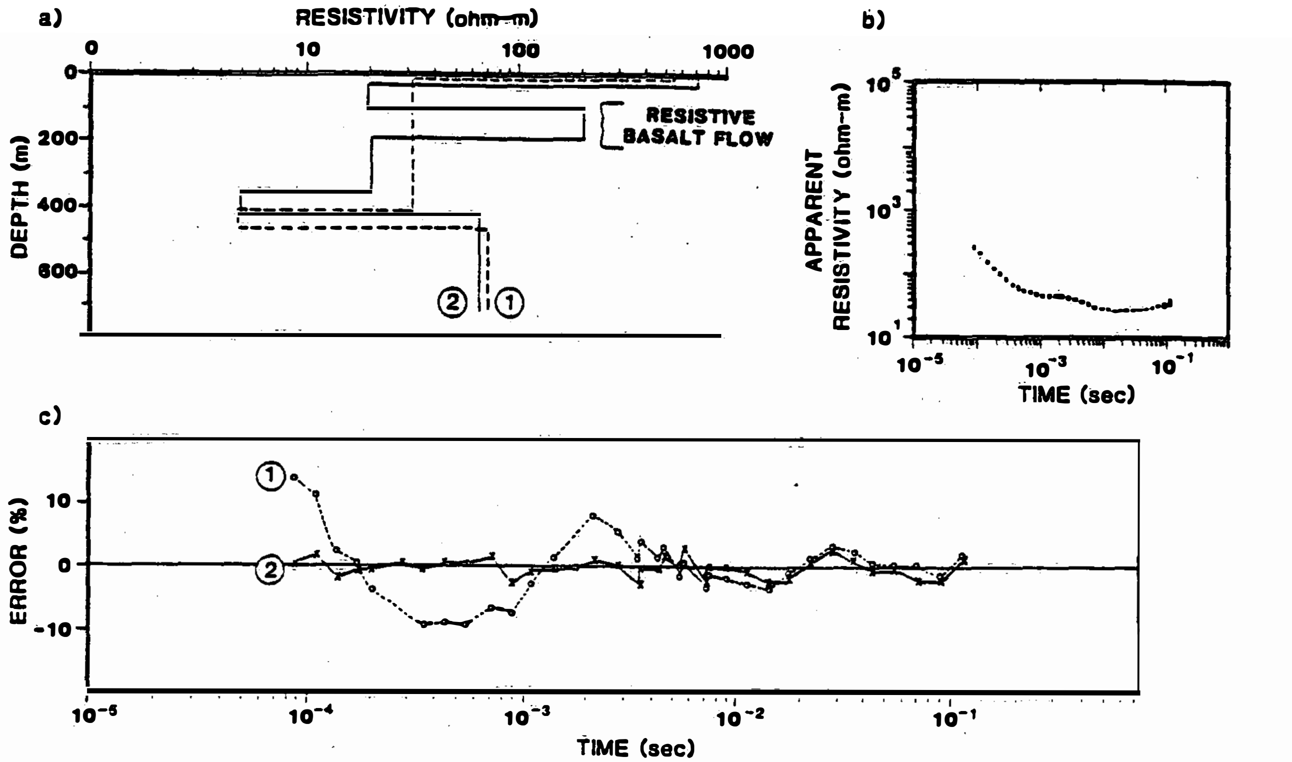


FIG. 7. Geoelectric sections (a) derived from 1-D inversions of measured apparent resistivity curve (b) over Tertiary Valley fill in Nevada. For each geoelectric section error of inversion is shown as function of time (c).

Validity of One-Dimensional Interpretation

The complexity of evaluating the influence of 2-D and 3-D structures of TDEM data is often cited as a disadvantage (Goldman, 1988). Indeed, currently, computations of 2-D and 3-D structures require computations that cannot be economically and practically applied in routine exploration programs. From the 2-D and 3-D computations (Newman et al., 1987) that have been published, important conclusions can be derived about the validity of 1-D interpretations in the presence of 2-D and 3-D structures. For example, Newman et al. (1987) computed the response over a resistive and conductive 3-D structure buried in a layered half-space at a depth of about 300 m. They reached the conclusion that 1-D inversions gave good estimates of the depth of burial of the 3-D structure, but unreliable depth extent and resistivities of the 3-D body. They used relatively large transmitter loops (1000 m by 1000 m) compared to exploration depth (1000 m) in their computations.

Drill-hole control is seldom sufficient to evaluate thoroughly the influence of 2-D and 3-D structures on a data set. Our experience, based on several thousand soundings with transmitter loop dimensions varying from 30 m by 30 m to 500 m by 500 m, is that 1-D interpretations yield good depth interpretations in the vast majority of work undertaken. Nevertheless, practical algorithms for data interpretation in the presence of 2-D and 3-D structures is an important need in TDEM soundings. Some efforts in that direction are promising (James, 1988).

Case Histories

Case History—High Level Nuclear Waste Repository Siting

The storage panels of the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico are being mined in the bedded salts of the Salado formation at a depth of about 600 m below ground surface. Underlying the Salado formation is the Castile formation, which is composed primarily of anhydrite and halite. It is known from oil and gas drilling that the Bell Canyon formation, underlying the Castile formation, can contain brines (Barrows et al., 1982).

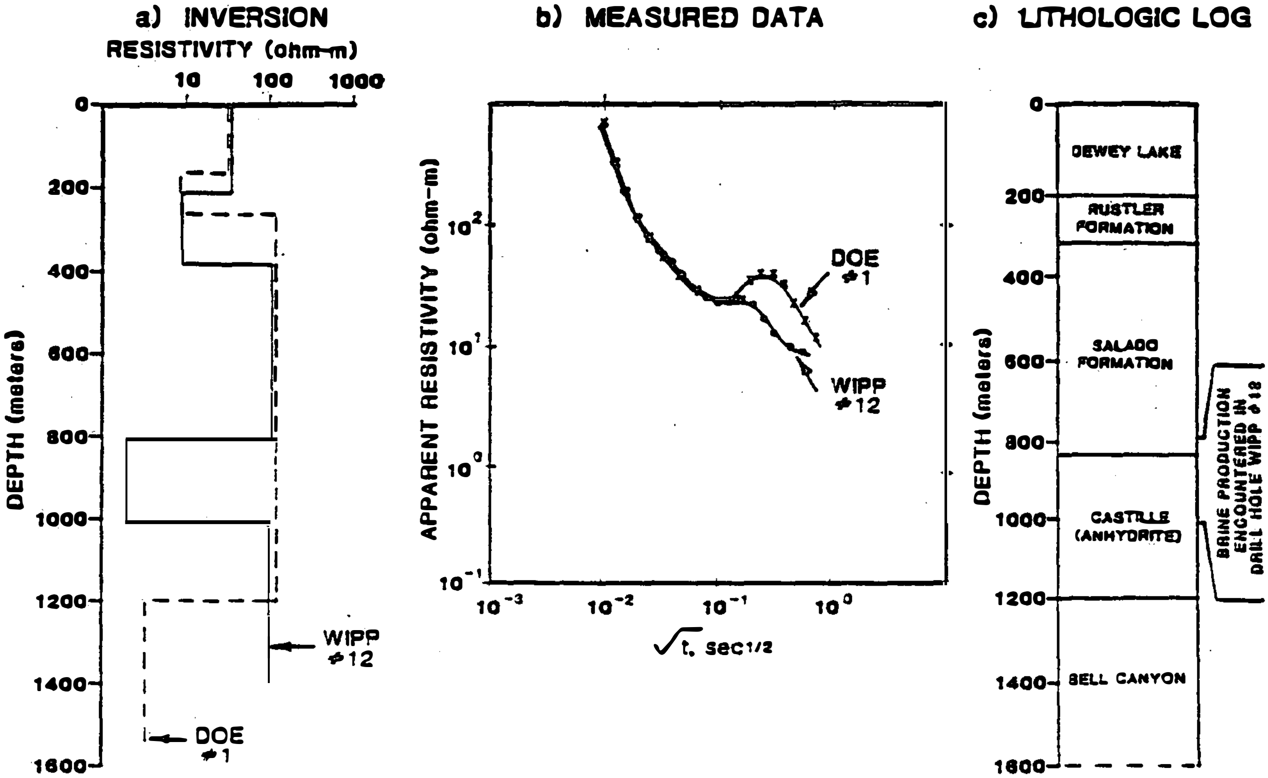


FIG. 8. Two measured late-stage apparent resistivity curves (b) and corresponding geoelectric sections derived from 1-D inversions (a). Also shown is a lithologic log common to both sounding locations (c).

The concept for placing a high level nuclear waste (HLW) repository in bedded salts at 600 m is to exploit the low hydraulic permeabilities of overlying bedded salts, and underlying anhydrites and halites. However, in the general vicinity of Carlsbad, New Mexico, drill holes encountered pressurized brine reservoirs at depths between 730 m and 915 m in the Castille formation (Register, 1981). The objective of TDEM surveys was to map the depth of first occurrence of brine over the waste storage panels and surrounding area.

A TDEM survey was conducted on a 500 m grid using central loop TDEM soundings over the waste storage panels and at selected drill hole locations. The transmitter loop dimensions employed were 500 m by 500 m and the TDEM equipment used was the Geonics EM-42. Figure 8b shows two apparent resistivity curves located within 150 m of two drill hole locations, WIPP #12 and DOE #1. The resistivity layering derived from 1-D inversions for these two soundings is given in Figure 8a, and Figure 8c shows a lithologic log common to WIPP #12 and DOE #1. In the drilling of WIPP #12, brines were encountered at a depth of 850 m, and in drill hole DOE #1 no brines were encountered to total depth (TD = 900 m). The depth of first occurrence of brine observed in WIPP #12 is in excellent agreement with the depth of the low resistivity layer derived from the 1-D inversion of the adjacent TDEM sounding. Depth of occurrence of the low resistivity layer derived from the TDEM inversion near drill hole DOE #1 is at 1200 m, some 300 m below TD, and at a depth corresponding to the Bell Canyon formation.

The 1-D inversions of TDEM soundings over the waste storage panels showed first depth of occurrence of brine below 1050 m. This depth generally corresponds to the Bell Canyon formation. Thus, the 1-D interpretations of the depth of first occurrence of brine were consistent with available ground truth. A major concern remains the minimum dimensions of brine occurrences detectable with central loop soundings. This problem is being addressed by 2-D and 3-D forward modeling.

There are several other important objectives in environmental geophysics for mapping depth of first occurrences of brine, such as:

(1) Siting injection zones for oil field brines, and other liquid waste injection wells. Regulations require

injection zones to have a concentration of dissolved solids greater than 10 000 ppm and confining zones must separate US drinking water supplies (USDW) and injection zones (Federal Register, 1987).

(2) Monitoring migration of wastes upward from injection zones along fractures, abandoned wells, or faulty casings (Fitterman et al., 1986).

Mapping Encroachment of Salt Water Into Fresh-Water Aquifers

Intrusion of salt water in coastal aquifers often has as its main cause excessive withdrawal of ground water. It has long been recognized that surface electrical or electromagnetic methods can be effective in mapping fresh water—salt water interfaces (Flathe, 1964). Here, the application of TDEM surveys for this purpose is illustrated by a case history from the Salinas Valley, CA (Mills et al., 1988). A schematic hydrogeologic cross-section of the study area is given in Figure 9. There are four aquifer zones (1) a perched aquifer in which the ground water is heavily contaminated by fertilization, (2) a 180 ft aquifer approximately 60 m thick in which salt water has intruded under about 15 000 acres, (3) a 400 ft aquifer in which salt-water intrusion has been observed under about 6600 acres, and (4) a 900 ft aquifer in which no salt-water intrusion has yet been observed.

Thus, salt-water intrusion has progressed farthest inland into the 180 ft aquifer, so that to map water quality in the 400 ft aquifer requires exploration through a 180 ft aquifer containing high concentrations of dissolved solids. This information was used in designing the survey. To map salt-water encroachment in the 180 ft aquifer 100 m by 100 m transmitting loops were em-

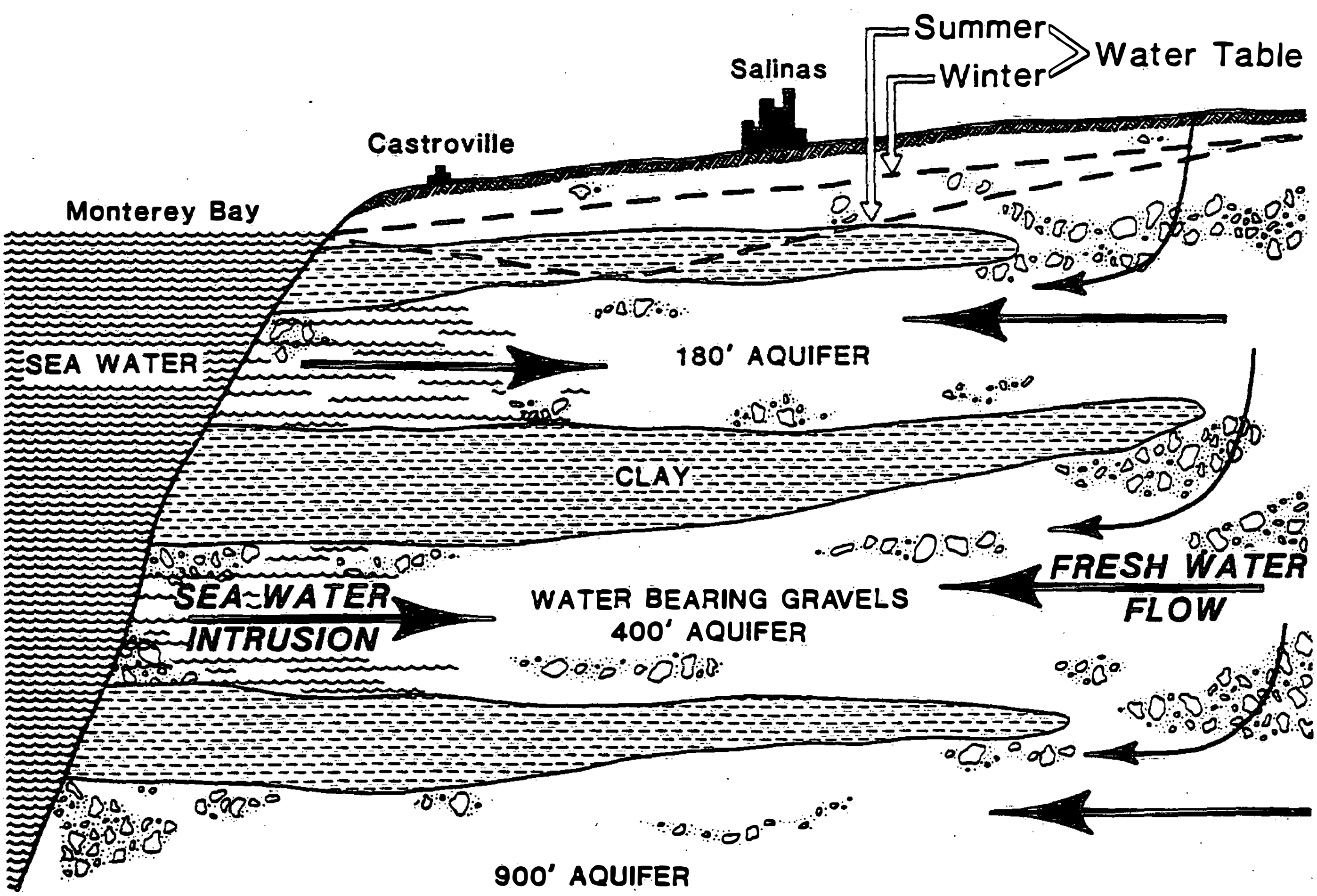


FIG. 9. Schematic hydrogeologic section of study area in the Salinas Valley, CA.

ployed. These transmitting loop dimensions provided sufficient field strength to derive the resistivity variation in the 180 ft aquifer. Larger transmitting loop dimensions (200 m by 200 m) were employed for exploration in the 400 ft aquifer. Approximately 100 stations were measured.

A series of four late-stage apparent-resistivity curves along cross-section B-B′ (Figure 12) are shown on Figure 10 along with geoelectric sections derived from 1-D inversions. Figure 11 shows the geoelectric section derived from TDEM soundings along profile B-B′. In the 180 ft aquifer the resistivity gradually increases inland from 1.5 $\Omega \cdot$m (station L24/3) to 18 $\Omega \cdot$m (station L10/1). In the 400-ft aquifer the resistivity increased from 5.0 $\Omega \cdot$m to in excess of 20 $\Omega \cdot$m.

Information from monitoring wells maintained by the Monterey County Flood Control and Water Conservation District was used to help constrain the number of layers used for the inversions of the TDEM data, and to correlate formation resistivities with equivalent chloride concentration. Correlation of formation resistivities with chloride concentration showed that a resistivity of approximately 8 $\Omega \cdot$m corresponds to a 500 ppm chloride concentration. Figure 12 shows the surface projection of the 500 ppm isochlor contours (8 $\Omega \cdot$m formation resistivity) in the 180 ft and 400 ft aquifers. The 500 ppm isochlor, based on monitoring wells, is also shown. There is more detail in the contours derived from the TDEM surveys mainly because of the higher station density.

These types of TDEM surveys have now been performed in several areas of Florida (Steward and Gay, 1981), Massachusetts (Fitterman and Hoekstra, 1982), California (Mills et al., 1988), and New York. Important advantages of TDEM soundings in these surveys are:

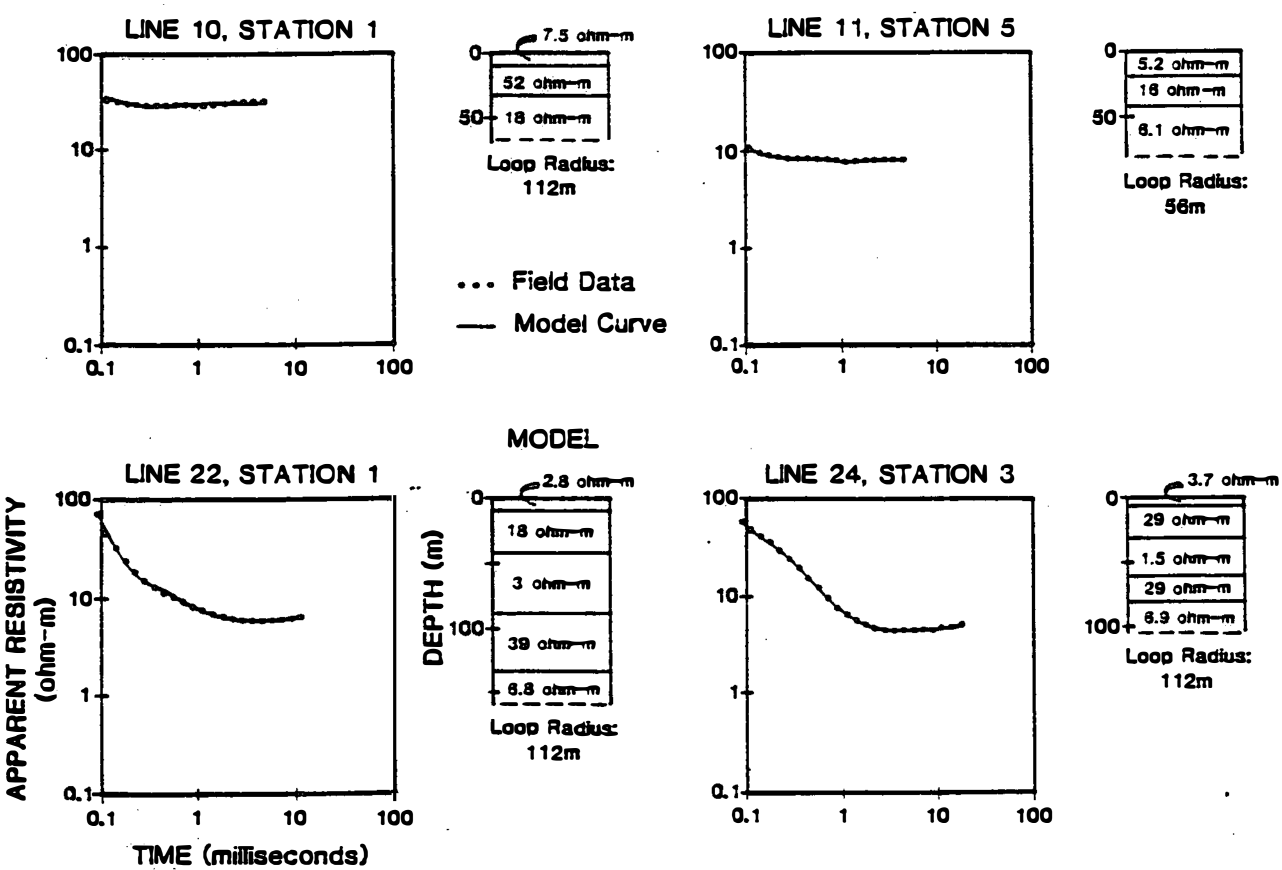


FIG. 10. Four apparent resistivity curves and inverted geoelectric sections along section B-B′ (Figure 12).

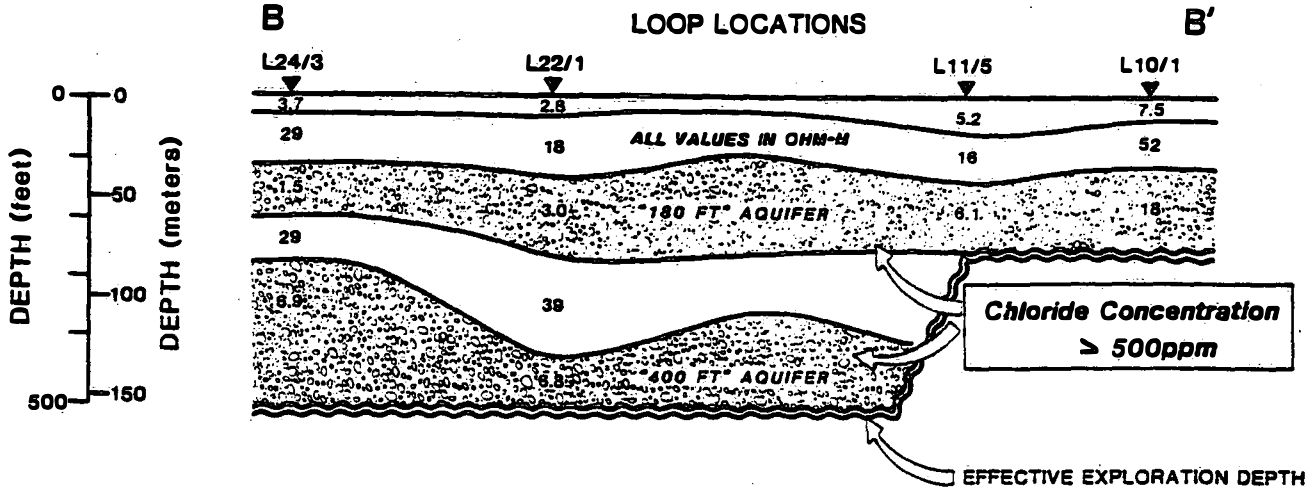


FIG. 11. Geoelectric section B-B′ derived from TDEM soundings.

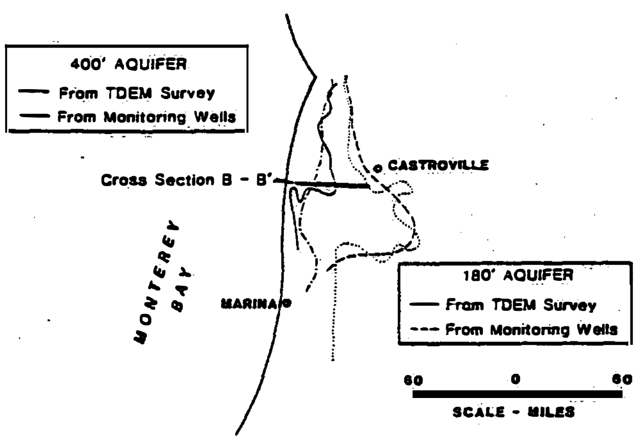


FIG. 12. Comparison of position of 500 ppm isochlor in 180 ft and 400 ft aquifers derived from monitoring wells and TDEM soundings.

(1) Coastal areas are often urbanized and limited space is available for measurements. TDEM measurements were often made in available open spaces such as high school athletic fields and parks.
(2) Ambient electrical noise (e.g., powerlines and radio stations) is high in developed areas. The signal stacking used in TDEM has proven an effective way for recovering signal from noise.

The utility of TDEM surveys for water management plans are in (1) providing optimum location for placement of monitoring and production wells, (2) determining depth of completion of such wells, (3) interpolating the position of the fresh water–saline water interface between wells, and (4) monitoring the movement of the interface over time. Geophysical stations can be moved from year to year, while monitoring wells lose some of their usefulness once the fresh water–saline water interface has migrated past their locations.

Shallow TDEM Surveys

Important exploration objectives for shallow (< 50 m) electrical exploration in environmental geophysics are

mapping continuity of confining layers, such as clay lenses;

mapping the presence of contaminants (e.g., originating from brine ponds) and pathways for migration of contaminants, such as fractures and shear zones;

correlating hydraulic transmissivities to electrical conductance (e.g., Huntley, 1986).

The geophysical methodologies applied to these exploration problems have mainly been dc resistivity soundings (e.g., Evans et al., 1982) and frequency-domain electromagnetic conductivity profiling (e.g., McNeill, 1982). With the recent availability of a TDEM system (Geonics EM-47) for shallow exploration, some of these objectives are now within the exploration depth range of TDEM. An example of shallow central-loop soundings with a prototype EM-47 is a survey over relatively thin basalt flows near Golden, Colorado.

On North and South Table Mountain in Golden, Colorado, lava flows overlie the Denver formation. Figure 13a shows the geologic section of the upper 100 m on North Table Mountain (Waldschmidt, 1939). Figure 13c shows an apparent resistivity curve measured in the center of a 30 m by 30 m transmitter loop with the EM-47 and its 1-D inversion. A peak current of 2 A was driven through the loop, and the ramp turn-off (Figure 4a) was 2.5 μs. The first time gate was centered at 6.4 μs and data were collected at base frequencies of 300 Hz and 30 Hz. The geoelectric section derived from the 1-D inversion (Figure 13b) shows good agreement between geologic boundaries and breaks in resistivity.

For this geoelectric section and for 30 m by 30 m transmitter loops (R = 15 m), late stage commences at about 10^{-5} s (Figure 3), so that almost the entire measured curve is in late-stage. Also shown on Figure 13c are forward modeled curves with different thicknesses of the upper basalt flow, while all other parameters were held constant. Large changes in the curves occur mainly

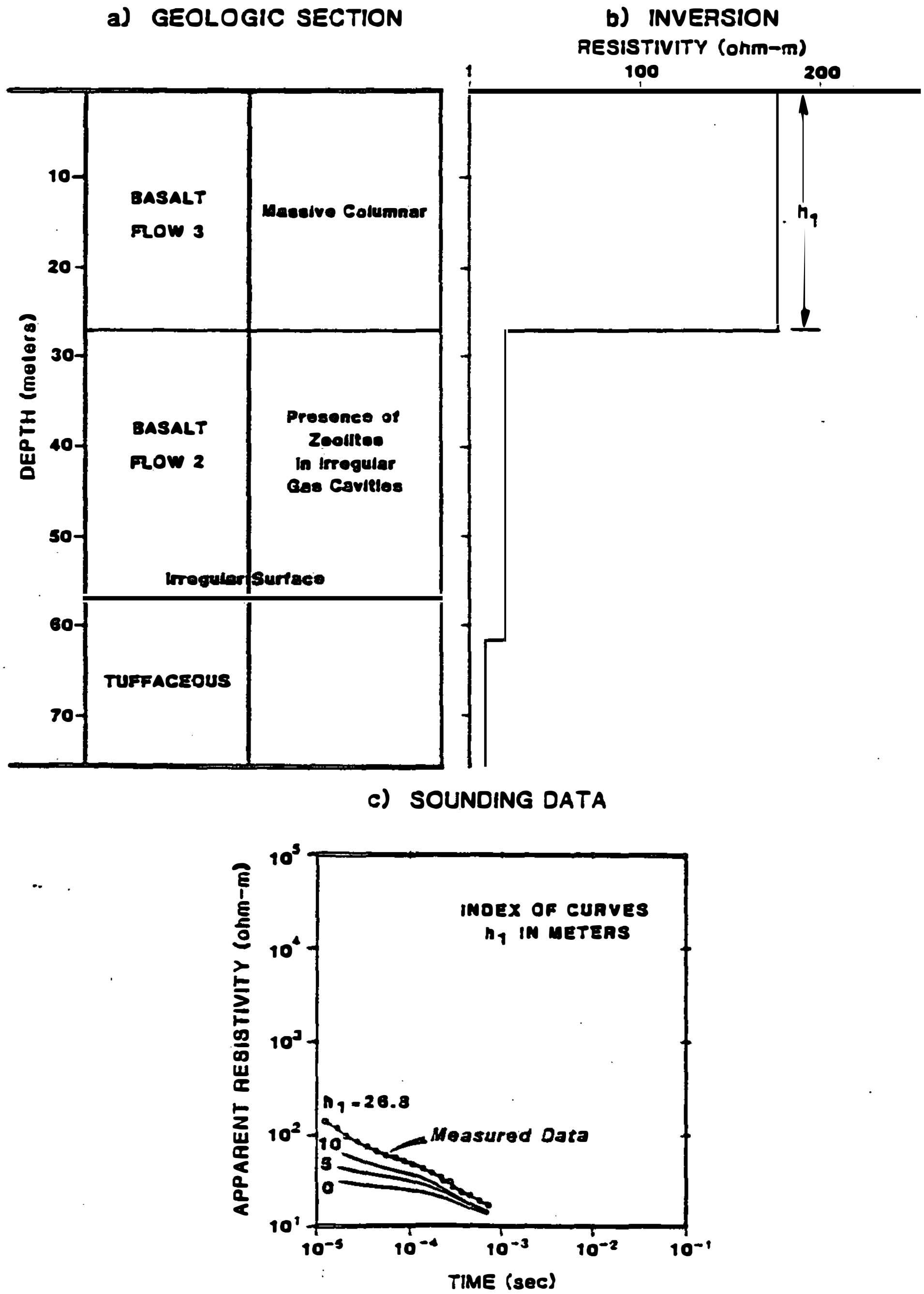


FIG. 13. (a) Geologic section of North Table Mountain, Golden, CO; (b); and geoelectric section derived from 1-D inversion of central loop sounding data with 30 m by 30 m transmitter loop; (c) the measured apparent resistivities are superimposed on a series of forward model curves in which the thickness of the upper basalt layer is varied.

over the time range from 10^{-5} s to 10^{-3} s; the time range covered by EM-47 measurements.

The conclusions from a number of conducted surveys is that the EM-47 can be employed in the depth range from 5 m to 75 m, depending somewhat on the geoelectric section. Since transmitter loop dimensions of 30 m by 30 m can be employed, survey productivity is high (30 to 50 stations per day). The TDEM EM-47 promises to be an effective methodology for electrical mapping in environmental geophysics, particularly in urban areas where space is limited and ambient noise is high.

Discussion

Focusing on the use of TDEM methods in environmental geophysics is such a narrow focus that there is a danger of overstating the utility of TDEM, compared to other electrical and electromagnetic measurement techniques. Raiche et al. (1985) and Fitterman et al. (1988) show that the range of equivalence in some geoelectric sections can in principle be reduced by combined use of dc resistivity and TDEM soundings. It is, therefore, important to note that the exploration objective in all three case histories consisted of determining depth to a conductive stratum, objectives optimally suited for electromagnetic techniques. TDEM surveys and other electromagnetic techniques have limitations for detecting thin resistive strata, and such limitations are readily evaluated by forward modeling.

One advantage of TDEM not evident from forward modeling computations is the absence of scatter in the data. The data scatter frequently observed in dc resistivity soundings, and distant source techniques (controlled source audiomagnetotelluric, audiomagnetotelluric, and magnetotelluric methods) are often due to lateral variation in resistivity and measurement of the electric field. The scatter is reduced in central loop TDEM soundings mainly because of the short source/receiver separation and measurement of the time derivative of magnetic fields. The apparent resistivity curves shown in these investigations are typical of a large number of stations. No smoothing of the data is performed before inversions.

The recent availability of a shallow TDEM system for the exploration depth range from 5 m to 75 m makes this technique suitable for such environmental studies as well-site protection programs, and mapping plumes of ground-water contamination. Contamination plumes are often confined to narrow zones, and the high lateral resolution possible with shallow central loop TDEM soundings allows definition of both the lateral and vertical extent of such plumes.

References

Barrows, L. J., Gonzalez, D. D., and Weart, W. D., 1982, Geotechnical field measurements for evaluation of the WIPP site: Inst. Elect. & Electron. Eng., Trans. Nuclear Science, **NS-29**, 239.

Ehrenbard, R. L., Hoekstra, P., and Rozenberg, G., 1983, Transient electromagnetic soundings for permafrost mapping: Proc. 4th Intl. Conf. Permafrost, Natl. Acad. Sci., 272.

Evans, R. B., Benson, B. C., and Rizzo, J. R., 1982, Systematic hazardous waste site assessments: Proc. Management of Uncontrolled Hazardous Waste Site Conference, Washington, DC.

Federal Register, 1987, EPA 40 CFR Parts 124, 144, 146, and 148, Under ground injection control program, **52**, 166, 32446.

Fitterman, D. V., Raab, P. V., and Frischknecht, F. C., 1986, Detection of brine contamination from injection wells using transient electromagnetic soundings: EPA EMSL, Las Vegas, NV.

Fitterman, D. V., Stanley, W. D., and Bisdorf, R. J., 1988, Electrical structure of Newberry Volcano, Oregon: J. Geophys. Res., **93**, B-9, 10119–10134.

Fitterman, D. V., and Stewart, M. T., 1986, Transient electromagnetic sounding for groundwater: Geophysics, **51**, 995–1005.

Fitterman, D. V., and Hoekstra, P., 1982, Mapping of salt water intrusion with transient electromagnetic methods: Proc. NWWA EPA Conf., Surface and Borehole Geophysical Methods in Ground Water Investigations, Las Vegas, NV.

Fitterman, D. V., Meekes, J. A. C., and Ritsema, I. L., 1988, Equivalence behavior of three electrical sounding methods as applied to hydrogeologic problems: Presented at the 50th Ann. Mtg. Eur. Assn. Expl. Geophys.

Flathe, H., 1964, New ways for interpretation of geoelectric resistivity measurements in the search for and delineation of aquifers: Internat. Assn. of Sci. Hydrology Bull., 9th year, **1**, 52.

Frischknecht, F. C. and Raab, P. V., 1984, Time-domain electromagnetic soundings at the Nevada test site, Nevada: Geophysics, **49**, 981–992.

Goldman, M. M., 1988, Transient electromagnetic inversion based on an approximate solution of the forward problem: Geophysics, **53**, 118–128.

Goldman, M. M., and Rabinovich, B. I., Eds., 1974, Album of theoretical curves for transient soundings in the near zone using the horizontal magnetic field: SNIIGGIMS Meth. Recomm. Issue 10.

Hohmann, G. W., 1988, Numerical Modeling for Electromagnetic Geophysics, in Electromagnetic Methods in Applied Geophysics, Vol. 1, Theory, Nabighian, M. N., Ed., Soc., Expl. Geophys.

Huntley, D., 1986, Relations between permeability and electrical resistivity in granular aquifers: Ground Water, **24**, 466.

Interpex Ltd. 1985, Automatic ridge regression time domain inversion, ARRTI.

James, B. A., 1988, Detection of tunnels by transient electromagnetic subsurface imaging: U.S. Geol. Surv. open-file rep. 88.

Kaufman, A. A., and Keller, G. V., 1983, Frequency and transient soundings: Elsevier Science Publ. Co., Inc.

Keller, G. V., Pritchard, J. I., Jacobson, J. J., and Harthill, N., 1984, Megasource time-domain electromagnetic sounding methods: Geophysics **49**, 993–1009.

McNeill, J. D., 1982, Electromagnetic resistivity mapping of contaminant plumes: *in* Proc. Nat. Conf. on Management of Uncontrolled Hazardous Waste Sites, Washington, DC.

Mills, T., Hoekstra, P., Blohm, M., and Evans, L., 1988, Time domain electromagnetic soundings for mapping sea water intrusion in Monterey County, CA: Ground Water, **26**, 771–782.

Nabighian, M. N., and Oristaglio, M. L., 1984, On the approximation of finite loop sources by two-dimensional line sources: Geophysics, **49**, 1027–1029.

Newman, G. A., Anderson, W. L., and Hohmann, G. W., 1987, Interpretation of transient electromagnetic soundings over three-dimensional structures for the central-loop configuration: Geophysics, J. R. Astr. Soc., **89**, 884.

Rabinovich, B. I., Surkov, V. S., and Mandel'baum, M. M., 1977, Electrical prospecting for porous reservoirs with oil and gas on the Siberian platform: Sov. Geol. 2.

Rabinovich, B. I., and Surkov, V. S., 1978, Results of the use of the ZSB method on the Siberian Platform: *in* Theory and use of electromagnetic field exploration geophysics, Acad Nauk SSSR, Novosobirsk, 318.

Raiche, A. P., and Gallagher, R. G., 1985, Apparent resistivity and diffusion velocity: Geophysics, **50**, 1628–1633.

Raiche, A. P., Jepp, D. L. B., Rutters, H., and Vozoff, K., 1985, The joint use of coincident loop transient electromagnetic and Schlumberger soundings to resolve layered structures: Geophysics, **50**, 1618–1627.

Register, J. K., 1981, Brine pocket occurrences in the Castile formation, southeastern New Mexico: WTSD-TME-30801, U.S. Dept. of Energy.

Spies, B. R., and Eggers, D. E., 1986, The use and misuse of apparent resistivity in electromagnetic methods: Geophysics, **51**, 1462–1471.

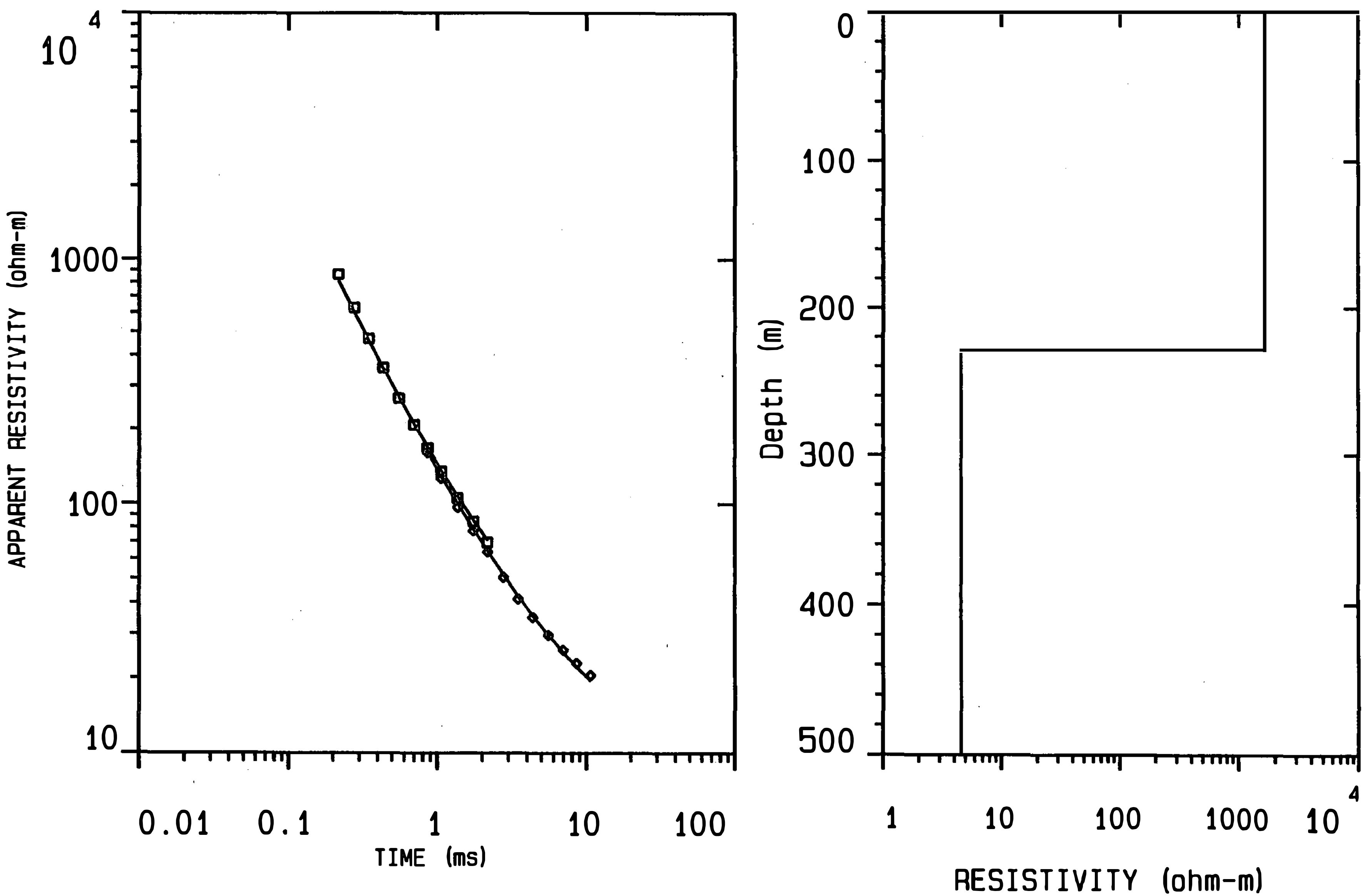
Stewart, M. T., and Gay, M., 1981, Evaluation of transient electromagnetic for deep detection of conductive fluids: Ground Water, **24**, 351.

Waldschmidt, W. A., 1939. The Table Mountain lavas and associated igneous rocks near Golden, Colorado: Quart. Col. School of Mines, **34**, No. 3.

Ward, S. H., and Hohmann, G. W., 1988, Electromagnetic theory for geophysical applications in electromagnetic methods: *in* Electromagnetic Methods in Applied Geophysics, Vol. 1, Theory, Nabighian, M. N., Ed. Soc. Expl. Geophys.

Wightman, W. E., Kaufman, A. A., and Hoekstra, P., 1983, Mapping gas-water contacts in shallow producing formations with transient EM: Presented at the 53rd Ann. Internat. Mtg., Soc. Expl. Geophys.

MAKEN-1



10^4
1000
100
10
APPARENT RESISTIVITY (ohm-m)
0.01
0.1
1
10
100
TIME (ms)
0
100
200
300
400
500
Depth (m)
1
10
100
1000
10^4
RESISTIVITY (ohm-m)

DATA SET: MAKEN-1

CLIENT: MAKENA RESORTS CORP DATE: 05-08-98
LOCATION: MAKENA, MAUI SOUNDING: 1
COUNTY: MAUI ELEVATION: 210.00 m
PROJECT: MAKENA IRRIGATION WELLS EQUIPMENT: Geonics PROTEM
LOOP SIZE: 213.000 m by 213.000 m AZIMUTH:
COIL LOC: 0.000 m (X), 0.000 m (Y) TIME CONSTANT: NONE
SOUNDING COORDINATES: E: 100.0000 N: 1.0000 SLOPE: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 3.876 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(FT)	CONDUCTANCE (Siemens)
			210.0	690	
1	1657.4	228.6	-18.60	-61	0.137
2	4.58				

ALL PARAMETERS ARE FREE

CURRENT: 14.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 7 RAMP TIME: 120.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.218	562.4	619.4	-10.12
2	0.278	495.2	526.6	-6.33
3	0.351	431.9	445.8	-3.20
4	0.438	372.0	377.2	-1.39
5	0.558	312.1	310.1	0.651
6	0.702	257.1	254.5	1.02
7	0.858	214.8	211.7	1.44
8	1.06	173.6	171.3	1.33
9	1.37	134.4	131.8	1.97
10	1.74	102.7	100.7	2.00
11	2.17	78.95	77.08	2.36

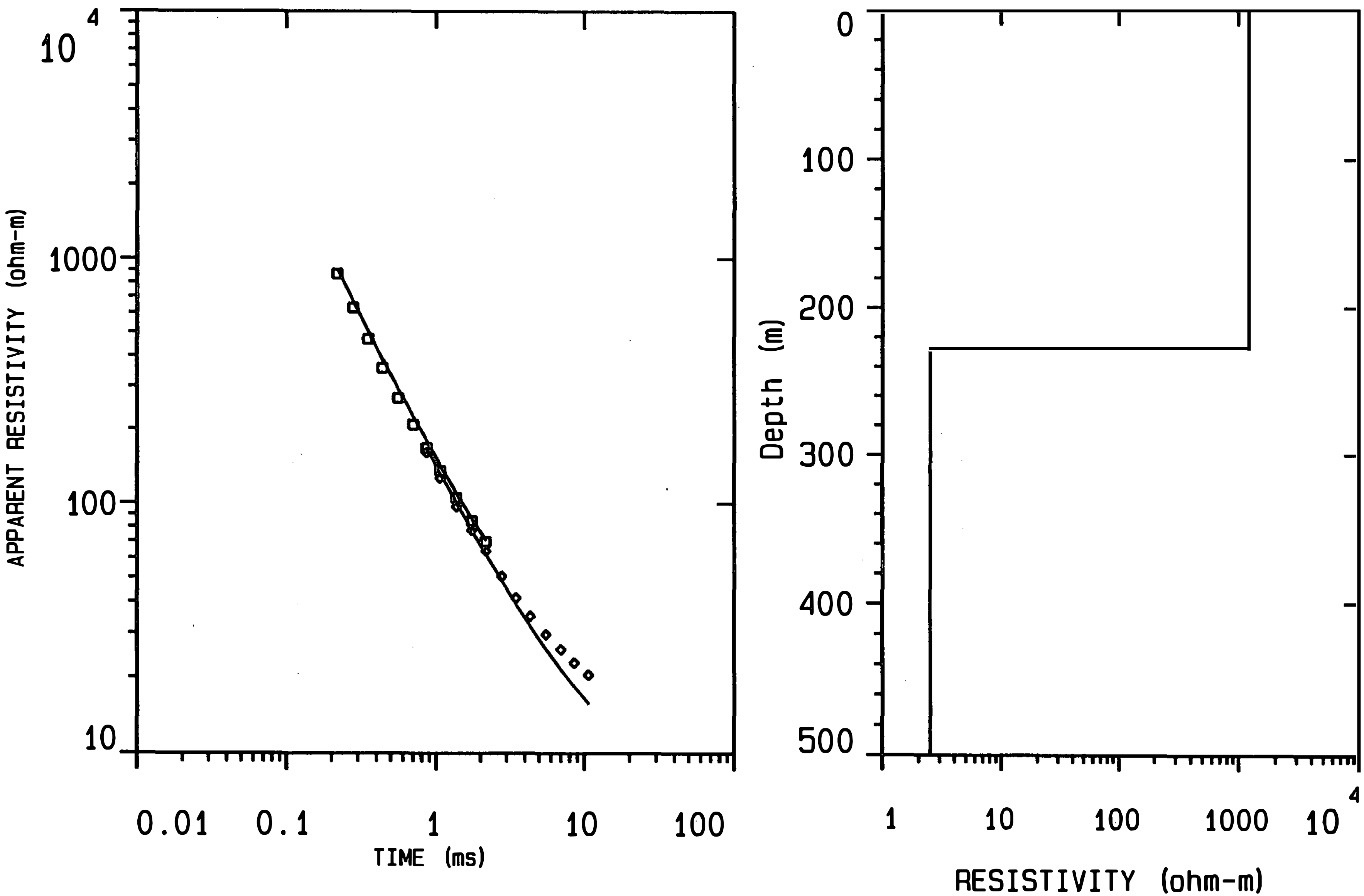
CURRENT: 14.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 7 RAMP TIME: 120.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
12	0.857	230.1	226.7	1.48
13	1.06	191.2	185.6	2.91
14	1.37	152.6	145.4	4.74
15	1.74	117.1	113.5	3.03
16	2.17	90.19	89.09	1.21
17	2.77	69.54	67.05	3.56
18	3.50	52.22	50.22	3.82
19	4.37	38.57	37.59	2.53
20	5.56	27.10	26.97	0.469
21	6.98	18.78	19.38	-3.22
22	8.56	13.56	14.20	-4.75
23	10.64	9.30	10.04	-7.94

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

P 1	0.01		
P 2	-0.03	0.90	
T 1	0.01	0.00	1.00
	P 1	P 2	T 1

MAKEN-1A



10^4
1000
100
10
APPARENT RESISTIVITY (ohm-m)
0.01
0.1
1
10
100
TIME (ms)
0
100
200
300
400
500
Depth (m)
1
10
100
1000
10^4
RESISTIVITY (ohm-m)

DATA SET: MAKEN-1A

CLIENT: MAKENA RESORTS CORP DATE: 05-08-98
LOCATION: MAKENA, MAUI SOUNDING: 1
COUNTY: MAUI ELEVATION: 210.00 m
PROJECT: MAKENA IRRIGATION WELLS EQUIPMENT: Geonics PROTEM
LOOP SIZE: 213.000 m by 213.000 m AZIMUTH:
COIL LOC: 0.000 m (X), 0.000 m (Y) TIME CONSTANT: NONE
SOUNDING COORDINATES: E: 100.0000 N: 1.0000 SLOPE: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 16.149 PERCENT

L #	RESISTIVITY (ohm-m)		THICKNESS (meters)	ELEVATION (meters)	(FT)	CONDUCTANCE (Siemens)
				210.0	690	
1	1204.1		227.3	-17.38	-57	0.188
2	2.50	*				

"*" INDICATES FIXED PARAMETER

CURRENT: 14.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 7 RAMP TIME: 120.00 muSEC

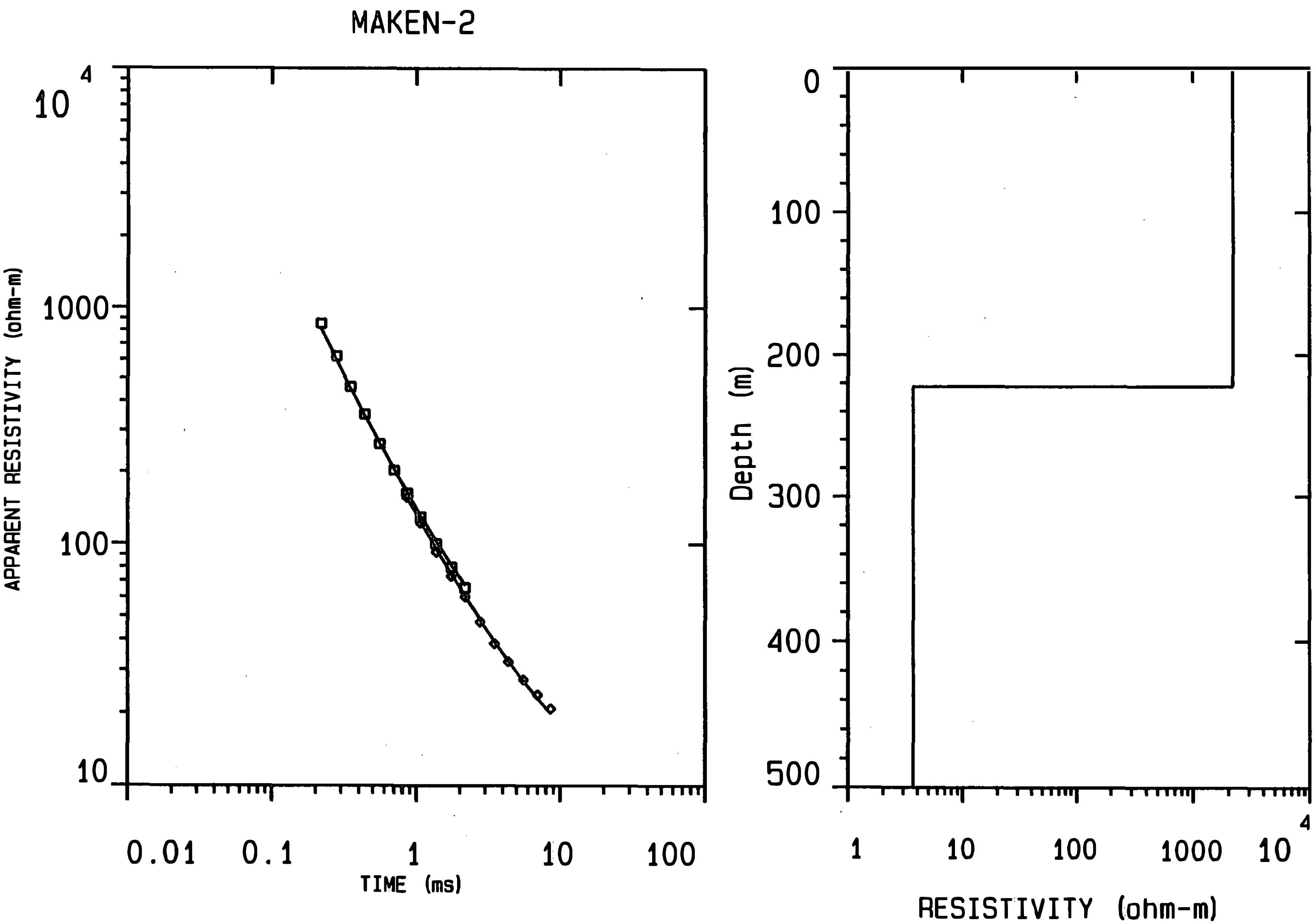
No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.218	562.4	526.5	6.38
2	0.278	495.2	451.0	8.94
3	0.351	431.9	386.2	10.58
4	0.438	372.0	330.2	11.23
5	0.558	312.1	275.7	11.66
6	0.702	257.1	229.9	10.56
7	0.858	214.8	194.3	9.53
8	1.06	173.6	160.3	7.64
9	1.37	134.4	126.4	5.99
10	1.74	102.7	99.13	3.55
11	2.17	78.95	77.84	1.40

CURRENT: 14.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 7 RAMP TIME: 120.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
12	0.857	230.1	214.4	6.82
13	1.06	191.2	179.6	6.03
14	1.37	152.6	144.9	5.09
15	1.74	117.1	116.6	0.396
16	2.17	90.19	94.34	-4.60
17	2.77	69.54	73.62	-5.87
18	3.50	52.22	57.19	-9.53
19	4.37	38.57	44.40	-15.10
20	5.56	27.10	33.17	-22.41
21	6.98	18.78	24.79	-31.99
22	8.56	13.56	18.81	-38.74
23	10.64	9.30	13.81	-48.41

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

	P 1	F 2	T 1
P 1	0.02		
F 2	0.00	0.00	
T 1	0.01	0.00	1.00



MAKEN-2
APPARENT RESISTIVITY (ohm-m)
10 4
1000
100
10
0.01
0.1
1
10
100
TIME (ms)
Depth (m)
0
100
200
300
400
500
1
10
100
1000
10 4
RESISTIVITY (ohm-m)

DATA SET: MAKEN-2

CLIENT: MAKENA RESORTS CORP DATE: 05-08-98
LOCATION: MAKENA, MAUI SOUNDING: 2
COUNTY: MAUI ELEVATION: 216.40 m
PROJECT: MAKENA IRRIGATION WELLS EQUIPMENT: Geonics PROTEM
LOOP SIZE: 213.000 m by 213.000 m AZIMUTH:
COIL LOC: 0.000 m (X), 0.000 m (Y) TIME CONSTANT: NONE
SOUNDING COORDINATES: E: 200.0000 N: 2.0000 SLOPE: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 3.758 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(FT)	CONDUCTANCE (Siemens)
			216.3	710	
1	2186.0	222.2	-5.87	-19	0.101
2	3.68				

ALL PARAMETERS ARE FREE

CURRENT: 13.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 7 RAMP TIME: 120.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.218	535.8	582.2	-8.65
2	0.278	468.9	498.0	-6.21
3	0.351	410.3	424.4	-3.42
4	0.438	353.7	361.0	-2.05
5	0.558	299.0	298.9	0.0167
6	0.702	248.9	246.9	0.810
7	0.858	210.3	206.7	1.71
8	1.06	172.7	168.5	2.42
9	1.37	135.1	130.7	3.25
10	1.74	104.3	100.7	3.38
11	2.17	80.78	77.81	3.67

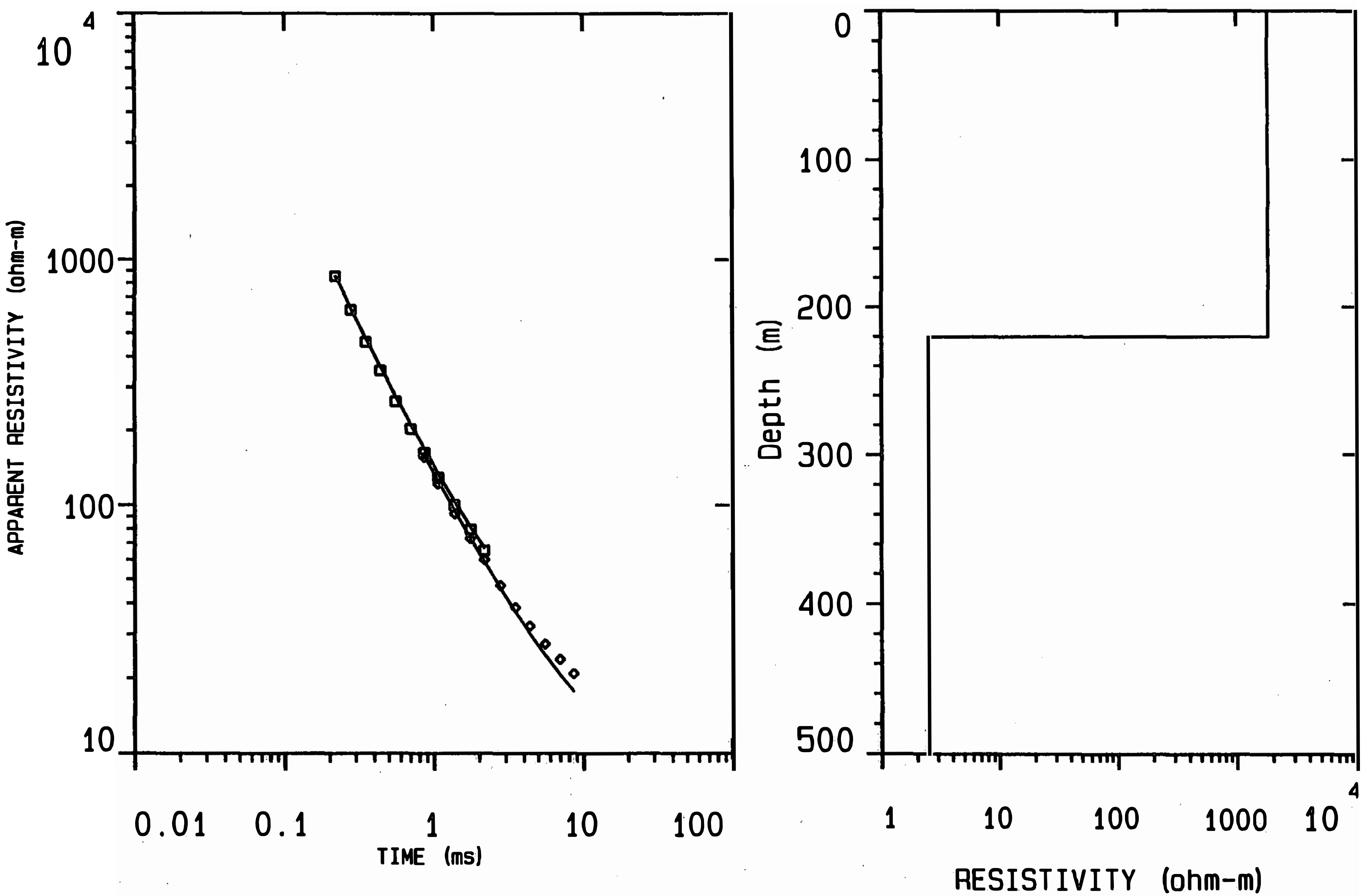
CURRENT: 13.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 7 RAMP TIME: 120.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
12	0.857	224.1	223.2	0.429
13	1.06	188.4	184.2	2.21
14	1.37	152.6	145.7	4.52
15	1.74	118.3	114.9	2.87
16	2.17	91.92	91.08	0.912
17	2.77	71.45	69.32	2.97
18	3.50	53.98	52.51	2.71
19	4.37	40.07	39.73	0.835
20	5.56	28.34	28.86	-1.84
21	6.98	19.86	20.97	-5.58
22	8.56	14.51	15.53	-6.99

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

P 1	0.00		
P 2	-0.02	0.87	
T 1	0.00	0.00	1.00
	P 1	P 2	T 1

MAKEN-2A



APPARENT RESISTIVITY (ohm-m)
10 4
1000
100
10
0.01
0.1
1
10
100
TIME (ms)
Depth (m)
0
100
200
300
400
500
1
10
100
1000
10 4
RESISTIVITY (ohm-m)

DATA SET: MAKEN-2A

CLIENT: MAKENA RESORTS CORP DATE: 05-08-98
LOCATION: MAKENA, MAUI SOUNDING: 2
COUNTY: MAUI ELEVATION: 216.40 m
PROJECT: MAKENA IRRIGATION WELLS EQUIPMENT: Geonics PROTEM
LOOP SIZE: 213.000 m by 213.000 m AZIMUTH:
COIL LOC: 0.000 m (X), 0.000 m (Y) TIME CONSTANT: NONE
SOUNDING COORDINATES: E: 200.0000 N: 2.0000 SLOPE: NONE

Central Loop Configuration
Geonics PROTEM System

FITTING ERROR: 9.483 PERCENT

L #	RESISTIVITY (ohm-m)	THICKNESS (meters)	ELEVATION (meters)	(FT)	CONDUCTANCE (Siemens)
			216.3	710	
1	1826.3	220.5	-4.11	-13.5	0.120
2	2.50 *				

"*" INDICATES FIXED PARAMETER

CURRENT: 13.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 30.00 Hz GAIN: 7 RAMP TIME: 120.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
1	0.218	535.8	528.8	1.29
2	0.278	468.9	454.8	2.98
3	0.351	410.3	390.4	4.84
4	0.438	353.7	334.5	5.42
5	0.558	299.0	279.6	6.46
6	0.702	248.9	233.3	6.25
7	0.858	210.3	197.2	6.19
8	1.06	172.7	162.7	5.76
9	1.37	135.1	128.2	5.14
10	1.74	104.3	100.4	3.75
11	2.17	80.78	78.76	2.49

CURRENT: 13.00 AMPS EM-37 COIL AREA: 100.00 sq m.
FREQUENCY: 3.00 Hz GAIN: 7 RAMP TIME: 120.00 muSEC

No.	TIME (ms)	emf (nV/m sqrd) DATA	SYNTHETIC	DIFFERENCE (percent)
12	0.857	224.1	217.1	3.11
13	1.06	188.4	181.8	3.48
14	1.37	152.6	146.4	4.05
15	1.74	118.3	117.7	0.532
16	2.17	91.92	95.06	-3.41
17	2.77	71.45	73.99	-3.55
18	3.50	53.98	57.34	-6.22
19	4.37	40.07	44.38	-10.75
20	5.56	28.34	33.06	-16.66
21	6.98	19.86	24.62	-23.93
22	8.56	14.51	18.63	-28.39

PARAMETER RESOLUTION MATRIX:
"F" INDICATES FIXED PARAMETER

P 1	0.01		
F 2	0.00	0.00	
T 1	0.00	0.00	1.00
	P 1	F 2	T 1